

Supplementary Information for Evidence on scaling forest restoration from the Atlantic Forest Restoration Pact in Brazil

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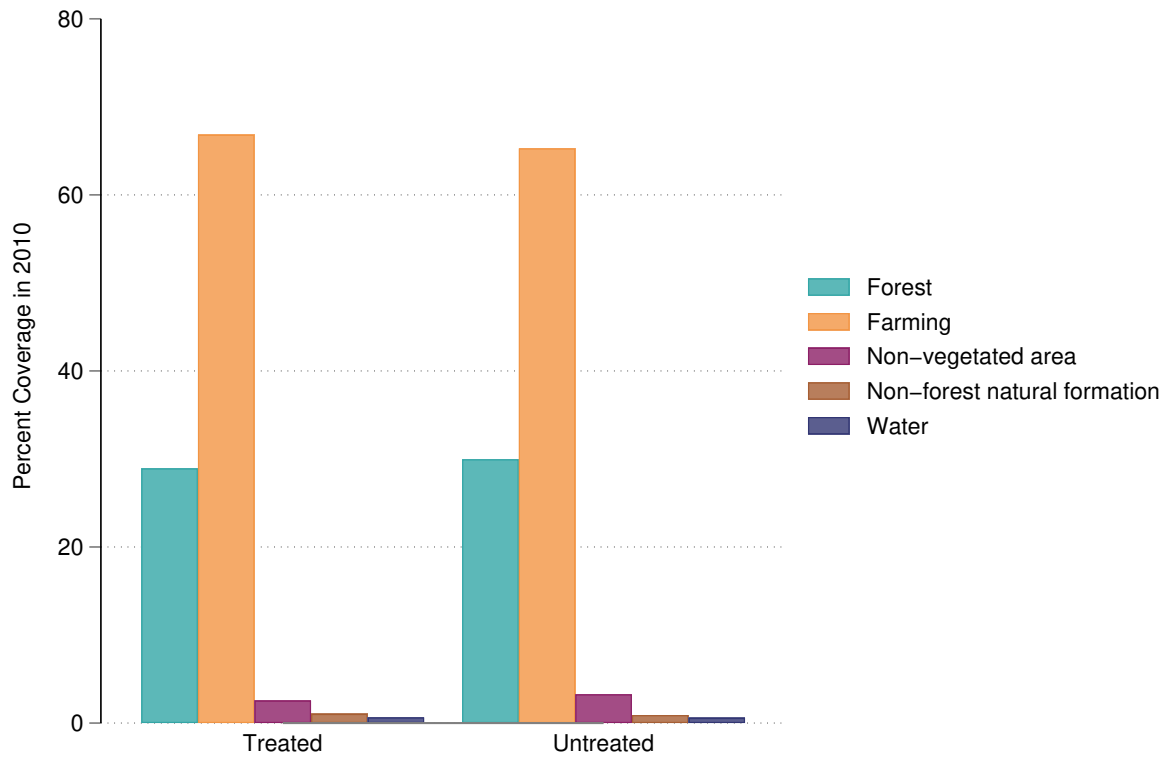
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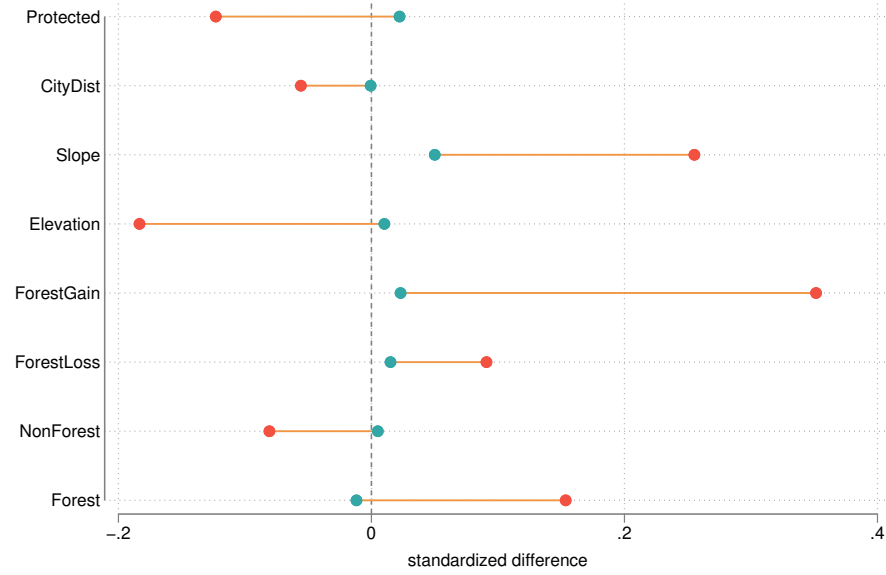
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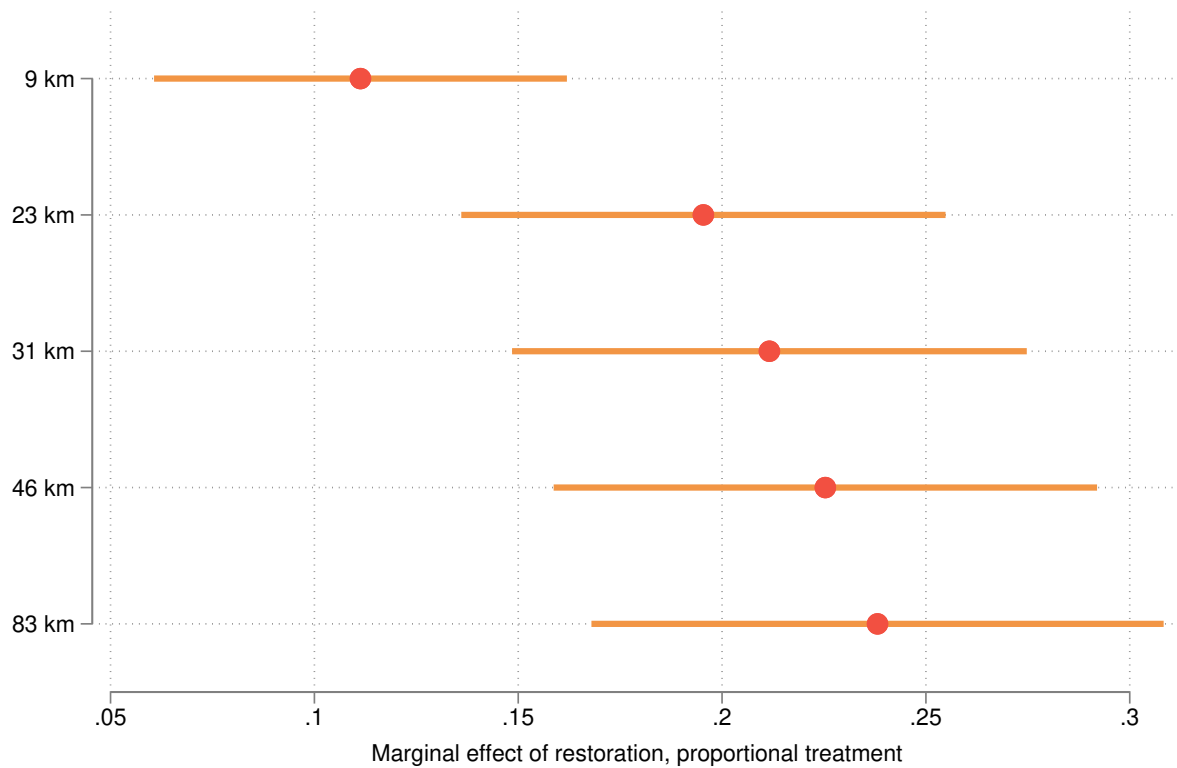
Supplementary Figures



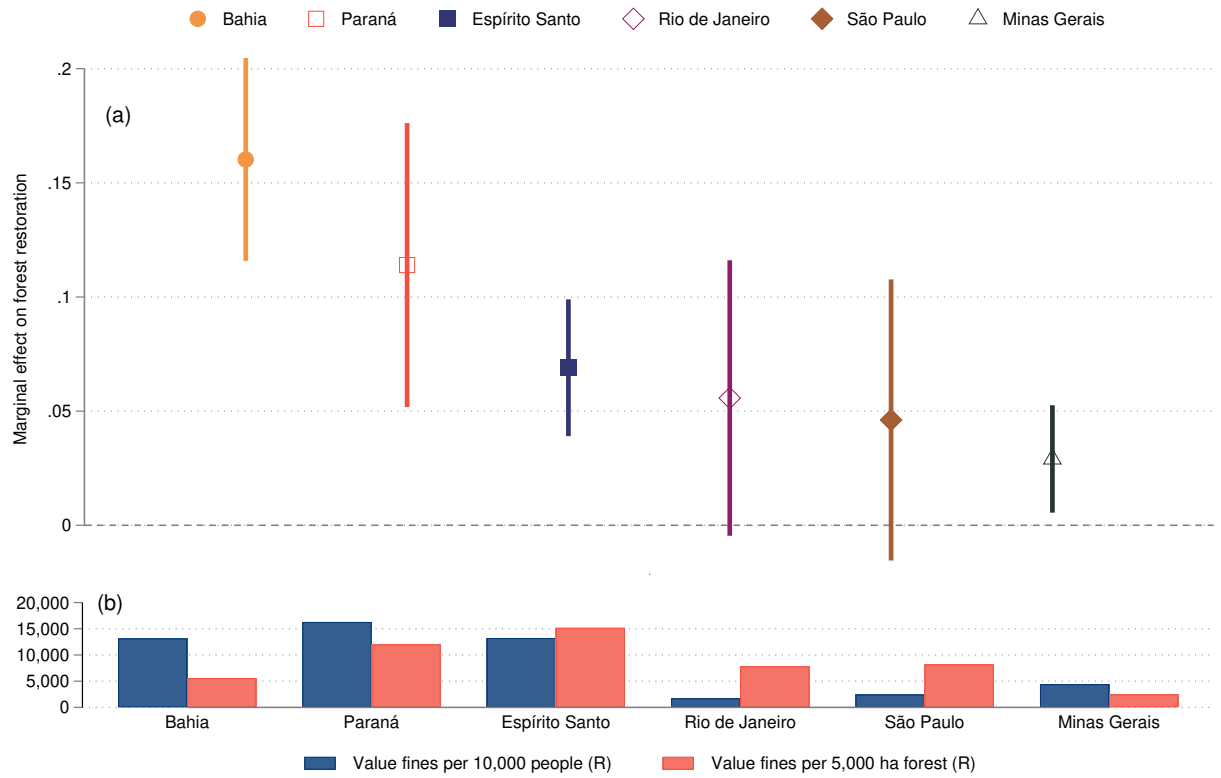
Supplementary Figure 1: **Land Cover in 2010.** Figure contains the average percentage of different land use types in MapBiomass 2010 land use classification, summarized within treated and matched control units.



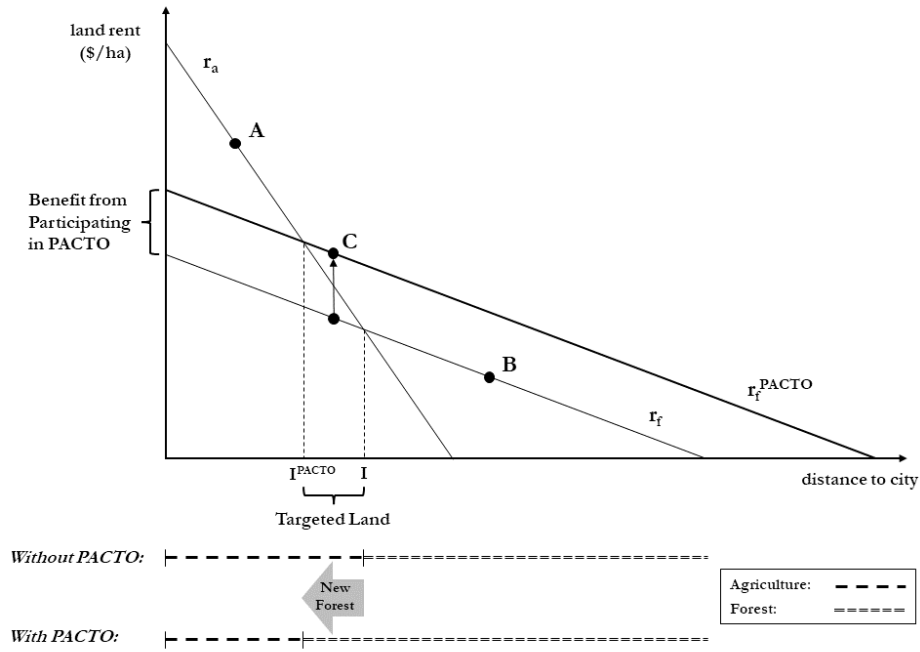
Supplementary Figure 2: **Improvements in covariate balance due to matching.** The points show standardized differences of observable factors between treated and untreated groups. Red points are standard differences before matching, blue points are standard differences after matching. Movement toward zero indicates that matching improved balance. “Protected” refers to the average occurrence of cells within a protected area that was designated as of 2000. “NonForest” and “Forest” refer to total area in 2000. “ForestGain” and “ForestLoss” denote forest cover change in the pre-treatment period of 2000 to 2009.



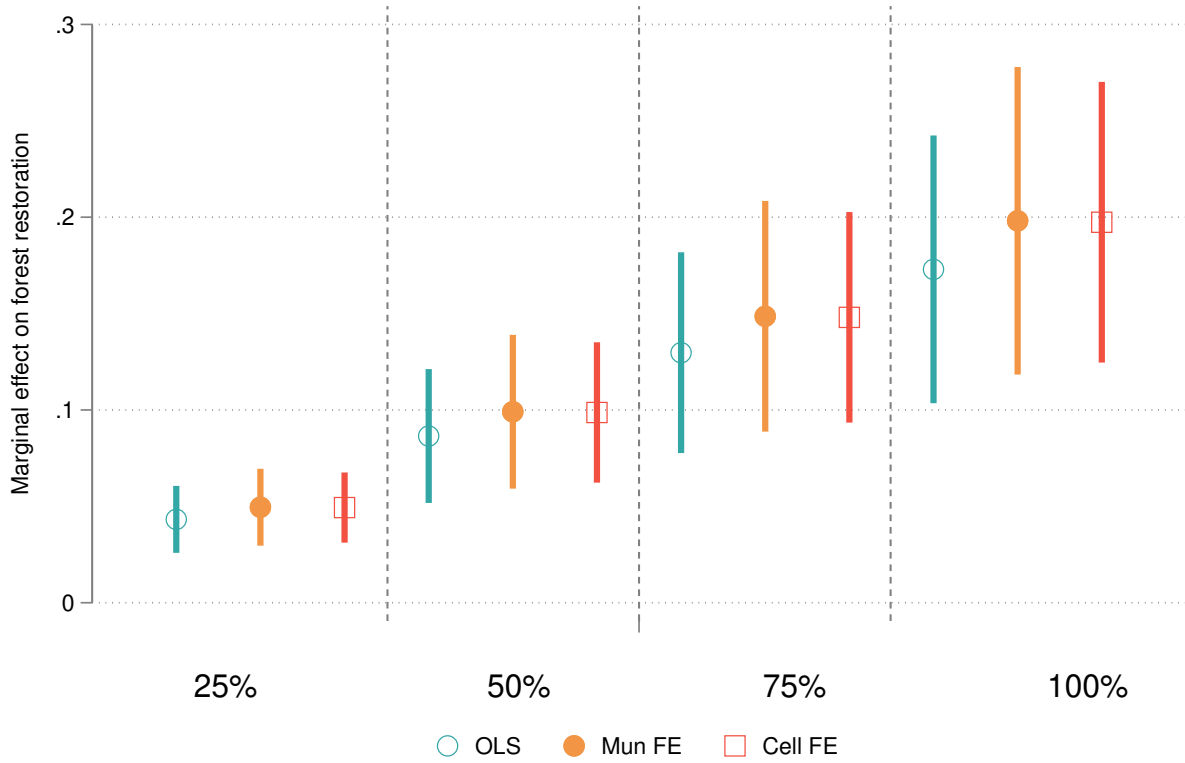
Supplementary Figure 3: **Restoration is least effective in close proximity to cities.** The x-axis shows the marginal effect of treatment using the proportional indicator of treatment interacted with 1 divided by 100 km to nearest city., so these can be interpreted as the impact of a grid cell being entirely enrolled in restoration. The y-axis shows different distances to city, where the marginal effects are calculated at these distances.



Supplementary Figure 4: **Impacts and fines are highest in the states of Bahia and Parana.** **a** shows the coefficient on the interaction between having any part of the analysis unit treated and the post period indicator using the estimates shown in Supplementary Table 2, columns (1)-(6). All estimations include unit fixed effects and time-varying controls. Markers denote the estimated coefficient and lines are 95% confidence intervals. **b** shows the value of forest-related fines per capita and forest-related fines per hectare of forest for each state in the sample between 2000 and 2018¹.



Supplementary Figure 5: **Restoration encourages a switch from agriculture to forest by raising net forest rent.** The adapted Von Thunen framework demonstrates how the benefits received from restoration leads profit-maximizing landowners to convert marginal (degraded) agricultural land to restored forest. The r^a curve represents agricultural land rent (\$ per ha), and the r^f curve represents land rent from restored forest (\$ per ha). In the interval of distance-to-city on the horizontal axis (between I and I^{PACTO}), agricultural land with initially marginally-higher rent than forest land (point C) is converted to restored forest when the benefit from PACTO shifts restored forest rent upward. The benefit from PACTO represents benefits to landowners (e.g., avoided fines, non-timber incomes, agroforestry, etc.), net of restoration costs. The same analysis applies to different land characteristics used for the horizontal axis, like slope and elevation.



Supplementary Figure 6: **Participation in PACTO increases area restored relative to baseline restorable area: additional specification checks.** This figure shows the interaction term between proportion of the analysis unit treated and the post period indicator. The results are from Supplementary Table 1, columns (4, 5, 6), which are an ordinary least squares estimation with different levels of fixed effects. The treatment variable in this case is continuous, and the dots indicate this treatment effect evaluated at 25, 50, 75 and 100% coverage of the analysis units in a restoration parcel. Markers denote marginal effects and lines are 95% confidence intervals



Supplementary Figure 7: **Annual net forest recovery for extended time series.** Average net forest recovery trends using outcomes from MapBiomass Collection 9 for all cells in post-matching treated (blue line) and untreated (dashed red line) groups are shown before and after treatment in 2009 (dashed line).

Supplementary Tables

Supplementary Table 1: Participation in PACTO increased restoration

	Binary treatment			Proportional treatment		
	(1)	(2)	(3)	(4)	(5)	(6)
Treat x Post	0.106*** [0.079,0.134] (0.000)	0.105*** [0.078,0.132] (0.000)	0.099*** [0.073,0.125] (0.000)			
Treat	0.007 [-0.007,0.021] (0.341)	0.010* [-0.002,0.022] (0.093)				
Prop. Treated x Post				0.173*** [0.104,0.242] (0.000)	0.198*** [0.118,0.278] (0.000)	0.197*** [0.125,0.270] (0.000)
Prop. Treated				0.009 [-0.021,0.039] (0.558)	0.002 [-0.021,0.026] (0.836)	
Post	-0.128*** [-0.184,-0.071] (0.000)	-0.080** [-0.143,-0.017] (0.014)	-0.022 [-0.079,0.036] (0.453)	-0.102*** [-0.160,-0.044] (0.001)	-0.055* [-0.119,0.009] (0.090)	-0.001 [-0.059,0.058] (0.984)
Observations	153974	153974	154220	153974	153974	154220
Mun FE	No	Yes	No	No	Yes	No
Cell FE	No	No	Yes	No	No	Yes

Note: This table reports three main specifications for post-matching difference-in-differences regression on the main sample, which excludes control units within 500m of a treated unit. Columns (1)-(3) use a binary treatment variable equal to 1 if any part of the cell is in a restoration polygon and columns (4)-(6) a treatment variable equal to the proportion of the cell in a restoration polygon. Each numbered column represents a separate estimation. The outcome is net hectares of forest recovered divided by hectares of initial non-forested area. Specifications vary by fixed effect choice (municipal or cell – indicated in the bottom two rows of the table). For the specifications with municipal fixed effects, included covariates are km to nearest city, population of nearest city, land surface categories, geologic categories, bioclimate categories, precipitation, and temperature. Only precipitation and temperature are included in the specifications with cell fixed effects as the other time-invariant covariates are absorbed by those fixed effects. * $p < .10$, ** $p < .05$, *** $p < .01$. Standard errors are clustered by municipality, confidence intervals are reported in [] and exact p-values from a two-sided t-test in (). Tests have not been adjusted for multiple hypothesis testing.

Supplementary Table 2: Restoration effectiveness varied by state: binary specification

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Full	Bahia	Esp Santo	Parana	Rio de Jan	Sao Paulo	Min Gerais
Treat	0.099***	0.160***	0.069***	0.114***	0.056	0.046	0.029*
x Post	[0.073,0.125]	[0.116,0.205]	[0.039,0.099]	[0.052,0.176]	[-0.005,0.116]	[-0.015,0.108]	[0.006,0.053]
	(0.000)	(0.000)	(0.000)	(0.001)	(0.069)	(0.134)	(0.017)
Post	-0.022	0.029	-0.449	-0.011	0.056	0.031	0.042
	[-0.079,0.036]	[-0.896,0.955]	[-1.028,0.129]	[-0.069,0.047]	[-0.017,0.128]	[-0.063,0.125]	[-0.022,0.106]
	(0.453)	(0.948)	(0.122)	(0.697)	(0.126)	(0.500)	(0.193)
Observations	154220	50564	30144	25746	20825	8809	18132

Note: This table reports post-matching difference-in-differences regression with unit fixed effects on the main sample, using a binary treatment variable equal to 1 if any part of the unit is in a restoration polygon. Each numbered column represents results from a separate estimation. The outcome is net hectares of forest recovered divided by hectares of initial non-forested area. The first column (1) represents the main sample across all states and columns (2)-(7) restrict the sample to the state listed in the table header. Precipitation and temperature are included as covariates. * $p < .10$, ** $p < .05$, *** $p < .01$. Standard errors are clustered by municipality, 95% confidence intervals are reported in [] and exact p-values from a two-sided t-test in (). Tests have not been adjusted for multiple hypothesis testing.

Supplementary Table 3: Restoration effectiveness varied by state: continuous treatment

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Full	Bahia	Esp Santo	Parana	Rio de Jan	Sao Paulo	Min Gerais
Prop. Treated	0.197***	0.363***	0.119	0.198*	0.062	-0.008	0.127**
x Post	[0.125,0.270]	[0.263,0.462]	[-0.038,0.276]	[0.033,0.364]	[-0.025,0.150]	[-0.219,0.202]	[0.034,0.219]
	(0.000)	(0.000)	(0.131)	(0.021)	(0.155)	(0.934)	(0.009)
Post	-0.001	0.070	-0.427	0.009	0.068	0.055	0.035
	[-0.059,0.058]	[-0.898,1.038]	[-0.976,0.123]	[-0.041,0.059]	[-0.002,0.139]	[-0.042,0.152]	[-0.020,0.090]
	(0.984)	(0.880)	(0.123)	(0.714)	(0.055)	(0.250)	(0.203)
Observations	154220	50564	30144	25746	20825	8809	18132

Note: This table reports post-matching difference-in-differences regression with unit fixed effects on the main sample, using a treatment variable equal the proportion of the cell in a restoration polygon. Each numbered column represents a separate estimation. The outcome is net hectares of forest recovered divided by hectares of initial non-forested area. The first column represents the main sample across all states and columns (2)-(7) restrict the sample to the state listed in the table header. Precipitation and temperature are included as covariates. * $p < .10$, ** $p < .05$, *** $p < .01$. Standard errors are clustered by municipality, 95% confidence intervals are reported in [] and exact p-values from a two-sided t-test in (). Tests have not been adjusted for multiple hypothesis testing.

Supplementary Table 4: Pre-Matching Covariate Means

	Untreated	Treated	Norm. diff	Var ratio
Post-treatment				
Net forest recovery (ha), 2010-2018	0.037	0.134	0.291	2.222
Forest recovery (ha), 2010-2018	0.076	0.193	0.390	2.548
Forest loss (ha), 2010-2018	0.039	0.059	0.096	1.226
Pre-treatment				
Net forest recovery (ha), 2000-2009	0.078	0.172	0.252	1.661
Forest recovery (ha), 2000-2009	0.112	0.217	0.296	1.737
Forest loss (ha), 2000-2009	0.035	0.046	0.059	1.144
Forest cover (ha), 2000	0.538	0.617	0.101	1.032
Forest cover (ha), 2010	0.574	0.732	0.199	1.025
Nonforest cover (ha), 2000	1.387	1.358	-0.034	0.954
Nonforest cover (ha), 2010	1.350	1.243	-0.128	0.941
Elevation (m)	408.022	345.081	-0.119	0.716
Slope (deg)	9.264	11.159	0.185	0.948
Protected area	0.122	0.085	-0.087	0.723
Distance to City (km)	38.224	37.189	-0.044	0.816
Observations	2023642	49243	4145770	4145770

Note: The first two columns report means for the variables listed for the sample of units that do not overlap with restoration polygons (column 1) and those that have any overlap with restoration polygons (column 2). The third column reports the normalized difference in means across the two groups, which can be interpreted as the magnitude of the difference in means in terms of the standard deviation of the variable. The final column reports the ratio of the variances in treatment versus matched controls. The untreated column contains the full sample of all possible cells that might be selected into the comparison group and excludes control units within 500m of treated units.

Supplementary Table 5: Post-Matching Covariate Means

	Untreated	Treated	Norm. diff	Var ratio
Post-treatment				
Net forest recovery (ha), 2010-2018	0.049	0.163	0.304	1.416
Forest recovery (ha), 2010-2018	0.116	0.217	0.311	2.023
Forest loss (ha), 2010-2018	0.067	0.053	-0.059	0.640
Pre-treatment				
Net forest recovery (ha), 2000-2009	0.202	0.209	0.017	0.913
Forest recovery (ha), 2000-2009	0.238	0.248	0.023	0.877
Forest loss (ha), 2000-2009	0.036	0.039	0.015	0.925
Forest cover (ha), 2000	0.421	0.413	-0.012	0.952
Forest cover (ha), 2010	0.553	0.569	0.022	0.941
Nonforest cover (ha), 2000	1.586	1.590	0.005	0.965
Nonforest cover (ha), 2010	1.454	1.434	-0.027	0.944
Elevation (m)	288.901	292.291	0.007	0.957
Slope (deg)	10.108	10.460	0.035	0.983
Protected area	0.074	0.080	0.016	1.073
Distance to City (km)	37.311	37.297	-0.001	0.980
Observations	37229	42056	158570	158570

Note: The first two columns report means for the variables listed for the sample of units that do not overlap with restoration polygons (column 1) and were selected by the matching algorithm, and those that have any overlap with restoration polygons (column 2). The third column reports the normalized difference in means across the two groups, which can be interpreted as the magnitude of the difference in means in terms of the standard deviation of the variable. The final column reports the ratio of the variances in treatment versus matched controls.

Supplementary Table 6: Test of statistical difference in pre-treatment trends

	(1)	(2)
	Linear	Quadratic
Year x Treat	0.000** [0.000,0.000] (0.009)	0.000 [-0.000,0.000] (0.875)
Year (Quad) x Treat		-0.000 [-0.000,0.000] (0.878)
Observations	792850	792850

Note: This table reports post-matching difference-in-differences regression with unit fixed effects on the matched sample in the period before 2010 using linear and quadratic trends. Each numbered column represents a separate estimation. The treatment variable is equal to 1 if any part of the cell is in a restoration polygon. The outcome is net hectares of forest recovered divided by hectares of initial non-forested area. Precipitation and temperature are included as covariates. * $p < .10$, ** $p < .05$, *** $p < .01$. Standard errors are clustered by municipality, 95% confidence intervals are reported in [] and exact p-values from a two-sided t-test in (). Tests have not been adjusted for multiple hypothesis testing.

Supplementary Table 7: Post-Matching Covariate Means, CEM matching

	Untreated	Treated	Norm. diff	Var ratio
Post-treatment				
Net forest recovery (ha), 2010-2018	0.038	0.128	0.253	1.443
Forest recovery (ha), 2010-2018	0.107	0.184	0.250	1.907
Forest loss (ha), 2010-2018	0.069	0.056	-0.056	0.697
Pre-treatment				
Net forest recovery (ha), 2000-2009	0.161	0.164	0.006	0.998
Forest recovery (ha), 2000-2009	0.180	0.182	0.005	0.999
Forest loss (ha), 2000-2009	0.018	0.018	-0.003	0.962
Forest cover (ha), 2000	0.570	0.569	-0.001	0.998
Forest cover (ha), 2010	0.680	0.688	0.010	0.996
Nonforest cover (ha), 2000	1.386	1.389	0.004	0.999
Nonforest cover (ha), 2010	1.277	1.271	-0.007	0.997
Elevation (m)	323.830	322.344	-0.003	0.997
Slope (deg)	10.077	10.141	0.007	0.989
Protected area	0.067	0.067	0.000	1.000
Distance to City (km)	38.134	38.509	0.016	0.948
Observations	40352	40352	161408	161408

Note: The first two columns report means for the variables listed for the sample of units that do not overlap with restoration polygons (column 1) and were selected by the CEM matching algorithm, and those that have any overlap with restoration polygons (column 2). The third column reports the normalized difference in means across the two groups, which can be interpreted as the magnitude of the difference in means in terms of the standard deviation of the variable. The final column reports the ratio of the treated to control variances.

Supplementary Table 8: Estimation of binary treatment effects using CEM sample

	(1)	(2)	(3)
Treat x Post	0.093*** [0.074,0.113] (0.000)	0.094*** [0.075,0.113] (0.000)	0.088*** [0.070,0.106] (0.000)
Post	-0.136*** [-0.190,-0.082] (0.000)	-0.124*** [-0.178,-0.069] (0.000)	-0.064** [-0.106,-0.021] (0.003)
Treat	0.003 [-0.002,0.007] (0.306)	0.003 [-0.001,0.008] (0.158)	
Observations	135785	135785	135954
Mun_FE	No	Yes	No
Cell_FE	No	No	Yes

Note: This table reports three main specifications for post-matching difference-in-differences regression on the main sample, using a binary treatment variable equal to 1 if any part of the unit is in a restoration polygon. Each numbered column represents a separate estimation. The outcome is net hectares of forest recovered divided by hectares of initial non-forested area. Specifications vary by fixed effect choice (municipal or unit). For municipal fixed effects, included covariates are km to nearest city, population of nearest city, land surface categories, geology categories, bioclimate categories, precipitation, and temperature. Only precipitation and temperature are included with unit fixed effects. * $p < .10$, ** $p < .05$, *** $p < .01$. Standard errors are clustered by municipality, 95% confidence intervals are reported in [] and exact p-values from a two-sided t-test in (). Tests have not been adjusted for multiple hypothesis testing.

Supplementary Table 9: Restoration effectiveness varied by state: binary specification with CEM sample

	(1)	(2)	(3)	(4)	(5)	(6)
	Bahia	Esp Santo	Parana	Min Gerais	Rio de Jan	Sao Paulo
Treat	0.121***	0.073**	0.044***	0.096**	0.064*	0.064**
x Post	[0.092,0.151]	[0.029,0.118]	[0.030,0.059]	[0.036,0.156]	[0.015,0.113]	[0.021,0.106]
	(0.000)	(0.002)	(0.000)	(0.003)	(0.013)	(0.005)
Post	0.088	-0.467	0.062***	0.001	0.030	-0.009
	[-0.904,1.079]	[-1.064,0.129]	[0.029,0.095]	[-0.077,0.079]	[-0.040,0.101]	[-0.055,0.038]
	(0.854)	(0.119)	(0.001)	(0.975)	(0.388)	(0.699)
Observations	46119	28979	17288	20736	15528	7304

Note: This table reports post-matching difference-in-differences regression with unit fixed effects on the main sample, using a binary treatment variable equal to 1 if any part of the unit is in a restoration polygon. The specification is as described in equation (1). The outcome is net hectares of forest recovered divided by hectares of initial non-forested area. Each column restricts the sample to the state listed in the table header. Precipitation and temperature are included as covariates. * $p < .10$, ** $p < .05$, *** $p < .01$. Standard errors are clustered by municipality, 95% confidence intervals are reported in [] and exact p-values from a two-sided t-test in (). Tests have not been adjusted for multiple hypothesis testing.

Supplementary Table 10: Participation in PACTO increased restoration: outcome: ha forest restored, binary treatment

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Full	Bahia	Esp Santo	Parana	Min Gerais	Rio de Jan	Sao Paulo
Treat	0.105***	0.176***	0.057***	0.045**	0.085***	0.073	0.114***
x Post	[0.077,0.132]	[0.130,0.221]	[0.030,0.084]	[0.017,0.074]	[0.041,0.130]	[-0.014,0.159]	[0.061,0.167]
	(0.000)	(0.000)	(0.000)	(0.003)	(0.001)	(0.098)	(0.000)
Post	-0.112***	-0.072	-0.427	0.008	-0.019	0.054	0.002
	[-0.153,-0.071]	[-1.407,1.262]	[-1.113,0.258]	[-0.058,0.074]	[-0.099,0.061]	[-0.084,0.192]	[-0.035,0.040]
	(0.000)	(0.911)	(0.211)	(0.815)	(0.625)	(0.430)	(0.896)
Observations	158570	51888	30632	18326	27560	21232	8932

Note: This table reports post-matching difference-in-differences regression with unit fixed effects on the main sample and in each state, using a treatment variable equal to 1 if a restoration polygon has any overlap with the grid cell. The specification is as described in equation 1 in the manuscript. The outcome is ha of forest recovered. The first column represents the main sample across all states and columns 2-7 restrict the sample to the state listed in the table header. Precipitation and temperature are included as covariates. * $p < .10$, ** $p < .05$, *** $p < .01$. Standard errors are clustered by municipality, 95% confidence intervals are reported in [] and exact p-values from a two-sided t-test in (). Tests have not been adjusted for multiple hypothesis testing.

Supplementary Table 11: Participation in PACTO increased restoration: outcome: ha forest restored, proportional treatment

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Full	Bahia	Esp Santo	Parana	Min Gerais	Rio de Jan	Sao Paulo
Prop. Treated	0.238***	0.456***	0.180	0.159**	0.120	0.067	0.211**
x Post	[0.139,0.336]	[0.331,0.582]	[-0.003,0.362]	[0.050,0.267]	[-0.001,0.240]	[-0.095,0.228]	[0.085,0.337]
	(0.000)	(0.000)	(0.053)	(0.005)	(0.052)	(0.406)	(0.002)
Post	-0.094***	-0.034	-0.417	0.003	0.002	0.074	0.035
	[-0.140,-0.049]	[-1.426,1.358]	[-1.070,0.237]	[-0.063,0.069]	[-0.073,0.077]	[-0.064,0.212]	[-0.008,0.078]
	(0.000)	(0.960)	(0.201)	(0.920)	(0.958)	(0.281)	(0.109)
Observations	158570	51888	30632	18326	27560	21232	8932

Note: This table reports post-matching difference-in-differences regression with unit fixed effects on the main sample across all states and for each state, using a treatment variable equal the proportion of the cell in a restoration polygon. The outcome is ha of forest recovered. The first column represents the sample across all states and columns 2-7 restrict the sample to the state listed in the table header. Precipitation and temperature are included as covariates. * $p < .10$, ** $p < .05$, *** $p < .01$. Standard errors are clustered by municipality, 95% confidence intervals are reported in [] and exact p-values from a two-sided t-test in (). Tests have not been adjusted for multiple hypothesis testing.

Supplementary Table 12: Non-linear treatment, interaction with baseline area, restoration over baseline farmland

	(1)	(2)	(3)
	Quadratic	Base NF	Over farm
Prop. Treated x Post	0.290*** [0.184,0.397] (0.000)	1.396*** [1.026,1.766] (0.000)	0.221*** [0.149,0.292] (0.000)
Prop treated ² x post	-0.115 [-0.276,0.046] (0.160)		
Post	-0.005 [-0.063,0.052] (0.853)	-0.638*** [-0.839,-0.437] (0.000)	0.014 [-0.051,0.078] (0.673)
% non-forest x post		0.009*** [0.006,0.012] (0.000)	
% non-forest x treat x post		-0.014*** [-0.017,-0.010] (0.000)	
Observations	154220	154220	148180

Note: This table reports post-matching difference-in-differences regression with unit fixed effects on the main sample, using a treatment variable equal the proportion of the cell in a restoration polygon. The table examines heterogeneity in treatment across treatment intensity (column 1), baseline non-forest area (column 2) and using a outcome of net hectares forest recovered divided by hectares of initial farmland rather than net hectares of forest recovered divided by hectares of initial non-forested area (as in columns 1 and 2). All columns use the main sample and include temperature and precipitation as covariates. * p < .10, ** p < .05, *** p < .01. Standard errors are clustered by municipality, 95% confidence intervals are reported in [] and exact p-values from a two-sided t-test in (). Tests have not been adjusted for multiple hypothesis testing.

Supplementary Table 13: Binary treatment estimation without 500m spillover buffer

	(1)	(2)	(3)
Treat x Post	0.099*** [0.070,0.128] (0.000)	0.098*** [0.070,0.127] (0.000)	0.095*** [0.067,0.123] (0.000)
Post	-0.121*** [-0.178,-0.064] (0.000)	-0.074* [-0.147,-0.000] (0.049)	-0.018 [-0.088,0.052] (0.616)
Treat	0.007 [-0.005,0.019] (0.251)	0.009 [-0.002,0.020] (0.115)	
Observations	156514	156514	156744
Mun_FE	No	Yes	No
Cell_FE	No	No	Yes

Note: This table reports three main specifications for post-matching difference-in-differences regression on the full sample without a spillover buffer, using a binary treatment variable equal to 1 if any part of the unit is in a restoration polygon. The outcome is net hectares of forest recovered divided by hectares of initial non-forested area. Specifications vary by fixed effect choice (municipal or cell). For municipal fixed effects, include covariates are km to nearest city, population of nearest city, land surface categories, geology categories, bioclimate categories, precipitation, and temperature. Only precipitation and temperature are included with unit fixed effects. * $p < .10$, ** $p < .05$, *** $p < .01$. Standard errors are clustered by municipality, 95% confidence intervals are reported in [] and exact p-values from a two-sided t-test in (). Tests have not been adjusted for multiple hypothesis testing.

Supplementary Table 14: Binary treatment estimation excluding potential matches within 1000m

	(1)	(2)	(3)
Treat x Post	0.097*** [0.071,0.122] (0.000)	0.095*** [0.069,0.121] (0.000)	0.092*** [0.067,0.116] (0.000)
Post	-0.117*** [-0.168,-0.067] (0.000)	-0.072* [-0.131,-0.013] (0.018)	-0.016 [-0.072,0.039] (0.560)
Treat	0.011 [-0.003,0.025] (0.127)	0.015* [0.002,0.027] (0.021)	
Observations	152564	152564	152809
Mun_FE	No	Yes	No
Cell_FE	No	No	Yes

Note: This table reports three main specifications for post-matching difference-in-differences regression on a matched sample which excludes potential matches within 1000m, using a binary treatment variable equal to 1 if any part of the cell is in a restoration polygon. The outcome is net hectares of forest recovered divided by hectares of initial non-forested area. Specifications vary by fixed effect choice (municipal or cell). For municipal fixed effects, include covariates are km to nearest city, population of nearest city, land surface categories, geology categories, bioclimate categories, precipitation, and temperature. Only precipitation and temperature are included with unit fixed effects. * $p < .10$, ** $p < .05$, *** $p < .01$. Standard errors are clustered by municipality, confidence intervals are reported in [] and exact p-values from a two-sided t-test in (). Tests have not been adjusted for multiple hypothesis testing.

Supplementary Table 15: Participation in PACTO increased restoration, Collection 9 outcomes

	Binary treatment			Proportional treatment		
	(1)	(2)	(3)	(4)	(5)	(6)
Treat x Post	0.102*** [0.066,0.138] (0.000)	0.101*** [0.064,0.138] (0.000)	0.098*** [0.061,0.135] (0.000)			
Treat	0.028*** [0.010,0.046] (0.003)	0.031*** [0.013,0.050] (0.001)				
Prop. Treated x Post				0.143*** [0.071,0.216] (0.000)	0.155*** [0.084,0.225] (0.000)	0.160*** [0.094,0.226] (0.000)
Prop. Treated				0.080*** [0.036,0.125] (0.001)	0.061*** [0.022,0.101] (0.003)	
Post	-0.125*** [-0.202,-0.048] (0.002)	-0.093 [-0.229,0.043] (0.178)	-0.031 [-0.164,0.103] (0.648)	-0.097** [-0.170,-0.023] (0.011)	-0.063 [-0.193,0.068] (0.342)	-0.003 [-0.130,0.125] (0.967)
Observations	144680	144680	144909	144680	144680	144909
Mun FE	No	Yes	No	No	Yes	No
Cell FE	No	No	Yes	No	No	Yes

Note: This table reports three main specifications for post-matching difference-in-differences regression on the sample with outcomes extended using MapBiomass Collection 9 (through 2021). Columns (1)-(3) use a binary treatment variable equal to 1 if any part of the cell is in a restoration polygon and columns (4)-(6) a treatment variable equal to the proportion of the cell in a restoration polygon. Each numbered column represents a separate estimation. The outcome is net hectares of forest recovered divided by hectares of initial non-forested area. Specifications vary by fixed effect choice (municipal or cell – indicated in the bottom two rows of the table). For the specifications with municipal fixed effects, included covariates are km to nearest city, population of nearest city, land surface categories, geologic categories, bioclimate categories, precipitation, and temperature. Only precipitation and temperature are included in the specifications with cell fixed effects as the other time-invariant covariates are absorbed by those fixed effects. * $p < .10$, ** $p < .05$, *** $p < .01$. Standard errors are clustered by municipality, 95% confidence intervals are reported in [] and exact p-values from a two-sided t-test in (). Tests have not been adjusted for multiple hypothesis testing.

Supplementary Table 16: Event Study

	(1)
	IHS(Net Recovery)
Year=2000 × Pct. Treated	-0.000008 [-0.000081,0.000064] (0.819030)
Year=2001 × Pct. Treated	-0.000033 [-0.000107,0.000041] (0.373364)
Year=2002 × Pct. Treated	-0.000049 [-0.000131,0.000034] (0.247894)
Year=2003 × Pct. Treated	-0.000010 [-0.000131,0.000112] (0.873655)
Year=2004 × Pct. Treated	0.000026 [-0.000060,0.000112] (0.556094)
Year=2005 × Pct. Treated	0.000085* [-0.000009,0.000179] (0.075860)
Year=2006 × Pct. Treated	0.000015 [-0.000072,0.000103] (0.728343)
Year=2007 × Pct. Treated	-0.000014 [-0.000115,0.000087] (0.785140)
Year=2008 × Pct. Treated	0.000057 [-0.000042,0.000155] (0.256644)
Year=2009 × Pct. Treated	0.000000 [0.000000,0.000000] (.)
Year=2010 × Pct. Treated	0.000063 [-0.000018,0.000144] (0.123808)
Year=2011 × Pct. Treated	0.000135*** [0.000035,0.000235] (0.008307)
Year=2012 × Pct. Treated	0.000221*** [0.000078,0.000365] (0.002770)
Year=2013 × Pct. Treated	0.000234*** [0.000102,0.000367] (0.000637)
Year=2014 × Pct. Treated	0.000251*** [0.000112,0.000391] (0.000487)
Year=2015 × Pct. Treated	0.000295*** [0.000112,0.000477] (0.001754)
Year=2016 × Pct. Treated	0.000241*** [0.000122,0.000361] (0.000100)
Year=2017 × Pct. Treated	0.000306*** [0.000198,0.000414] (0.000000)
Year=2018 × Pct. Treated	0.000299*** [0.000118,0.000480] (0.001327)
Observations	1506415

Note: This table reports estimates of an event study regression where the outcome is the inverse hyperbolic sign of net hectares of forest recovery, measured at the annual level from 2000 to 2018, omitting 2009 as the reference group. The estimation equation is given in the supplementary equation 1, which uses cell fixed effects, precipitation and temperature controls, year controls, and year and percent-treatment interactions. The table only reports the year and percent-treatment interactions. * $p < .10$, ** $p < .05$, *** $p < .01$. Standard errors are clustered by municipality, 95% confidence intervals are reported in [] and exact p-values from a two-sided t-test in (). Tests have not been adjusted for multiple hypothesis testing.

Supplementary Methods

This section contains additional discussion of the identification strategy, including consideration of spatial aggregation issues, matching, the counterfactual framework for causality, and regression specification choices.

Unit of analysis

We use a 2 hectare grid cell as our unit of analysis to capture the spatial window in which land use decisions are made. Doing so reduces estimation bias by aggregating spatial data to the scale that reflects both the area over which landowners are expected to choose alternate land uses Avenlino¹ and the scale at which relevant ecological processes can reasonably be measured². The finest-scale data we observe are 30m forest change and coverage pixels, which we aggregate to the 2 hectare cell with spatial averaging. Decisions relevant to the 2 hectare scale include (i) choosing land to restore and (ii) choosing land to deforest for productive use. Since the average restoration parcel in our sample is 7 hectares in size, our 2 hectare aggregation provides for 3.5 units of observation per parcel on average. This enables the measurement of heterogeneous decision-making across the property without introducing excess noise from finer scale data. The aggregation also helps reduce measurement error associated with 30m remote sensing data.

The original parcel dataset included over 30,000 polygons, but many of these were very small. We restrict our analysis to restoration parcels with more than two hectares of land in total due to concerns about measurement error of the impacts from very small restoration projects, which would partially overlap with multiple grid cells. Excluding these small areas means that our analysis will likely underestimate the true impact of PACTO, as some grid cells in the control group will actually be partially treated. However, the parcels analyzed capture more than 73% of the total area in the original database.

Matching and difference-in-differences estimation

We use matching to establish a set of counterfactual areas of land and difference-in-differences regression to isolate the treatment effect and further reduce bias that might enter the estimation due to unobservable differences across treatment and control parcels. The goal of

matching is (i) to create similar groups for comparison and (ii) to eliminate the influence of confounding variables³. Difference-in-differences regression controls for pre-trend differences as well as remaining treatment selection from fixed and time-variant factors. While no quasi-experimental method can fully substitute for randomization, identifying and controlling for key confounding variables allows the researcher to significantly reduce estimation bias and articulate the nature of potential remaining bias from unobservable characteristics.

Supplementary Table 4 shows covariate means for treated units and for the pool of all untreated units outside of 500m and within 5 km, prior to matching. We see that both groups experience less net forest recovery in the treatment period (due to a general decrease in forest recovery and increase in forest loss) from 2000 to 2019. On average, treated land has a slope of 11 degrees, 345 meters of elevation, and is 37km from the nearest city, while untreated land is less steeply sloped, higher in altitude, and farther from cities. The groups are also likely different with respect to unobservable characteristics, like landowner attitudes towards restoration. Comparing unlike groups could lead to erroneous conclusions. For example, a simple comparison of treatment versus all untreated areas would lead to an overestimate of the program’s success if the treated group is more inclined to restore forest.

To create a control group similar to treated land, we use propensity score matching, which selects the “nearest neighbor” counterfactual for each treated unit based on observables, as described in Methods. Matching variables are designed to capture the key potential confounding factors including agricultural productivity, forest ecology, land planning, institutional protection, and markets for forest goods. While these confounders are not directly observed, the observed matching variables act as their proxies. The matching variables are also in keeping with those used in similar conservation policy impact evaluations^{4–10}.

Before matching, there are 49,243 treated cells and a control pool of 2,023,642 untreated cells (Supplementary Table 4). During matching, 7,179 treated cells are excluded from the regressions due to lacking starting non-forest area (which is essential for the outcome measurement) or lack of common support in very small municipalities. After matching, the final dataset for analysis contains 42,056 treated cells and 37,229 untreated cells (Supplemen-

tary Table 5). Because matching is performed with replacement, 8,332 treated cells share a match with at least one other treated cell. After matching, pre-treatment forest recovery, land cover, elevation, slope, protected area overlap, and distance-to-city are all similar between groups (Supplementary Table 5 and Supplementary Figure 2). In the cross-section of land cover at the start of treatment, we also observe that the proportions of land in different land use types, including area in water, are very similar (Supplementary Figure 1).

Although the normalized mean differences and variance ratios suggest that the propensity score method leads to a balanced post-matching sample, we also implement “coarsened exact matching” (CEM)³ as a robustness check. The CEM results support our main conclusions (Supplementary Tables 7, 8, 9).

While matching creates similar groups, we further adjust for group differences over time using post-matching difference-in-differences (DID) regression. The impact of PACTO support is estimated by comparing the change in outcomes across the two groups before and after the intervention as described in Methods. The underlying assumption of this approach is that in the absence of the restoration program, land in the “treated” group would have followed the same time trend as the “untreated” group during the treatment period. Although this assumption cannot be directly tested, a test of whether this is true in the pre-treatment period provides support for its plausibility. Figure 3 demonstrates parallel trends in the pre-treatment period, as does our statistical test in Supplementary Table 6. The event study presented in the main text further demonstrates that prior to treatment, land in treated and control units was being managed similarly in terms of restoration behavior (Figure 5).

Equation 1 shows the post-matching difference-in-differences specification used to estimate the treatment effect of PACTO on forest recovery. β_1 represents the difference in recovery between the treated and the counterfactual group in the treatment period after controlling for municipality-level precipitation and temperature (V_{imt}) and cell fixed effects (λ_i). We include precipitation and temperature as key controls, as weather is an important ecological driver of forest change and we want to isolate forest change driven by restoration interventions. Cell fixed effects eliminate the confounding influence of unobservable fixed

characteristics at the unit level. These include slope, elevation, bioclimate, and soil type. In the specifications with municipal fixed effects, we include grid-cell measures of the first three of these variables. In addition, we know that landowner attitudes and networks are strong determinants of selection into restoration. To the extent that these attitudes are similar within spatial units and fixed over time, the municipal or cell fixed effects control for them.

As a robustness check, we also include an event study type estimation of the impact. Supplementary equation (1) specifies the estimation:

$$R_{imy} = \beta_0 + \sum_{y=2000}^{2008} \delta_y^{pre} D_i + \sum_{y=2010}^{2018} \delta_y^{post} D_i + \mathbf{V}_{imy}\alpha + \lambda_i + \gamma_y + \epsilon_{imy} \quad (1)$$

where R_{imy} measures net forest recovery, calculated as forest gain minus forest loss, in year y for cell i in municipality m . D_i denotes treatment defined as the proportion of the cell overlapping with a restoration parcel, and γ_y are year effects equals to 1 for each year in the data. $\mathbf{V}_{imy}$ includes temperature and precipitation as the time-varying controls. Cell fixed effects are given by λ_i . Cell fixed effects eliminate the influence of characteristics that do not change over time. These include important determinants of land productivity like slope, elevation, and bioclimate. ϵ_{imt} denotes the residual. The δ_y coefficient estimates the treatment effect on the treated group in each year, where years prior to 2009 constitute the pre-treatment period and years after 2009 the post-treatment period.

Limitations

Successful matching ensures that treated and control groups have land with similar qualities and alternative uses prior to treatment. The DID regression controls for remaining differences in pre-treatment forest trends as well as factors that affect group outcomes differently, both in a fixed sense (fixed effects) and over time (conditioning on weather). Nonetheless, some selection bias from PACTO’s targeting decisions and from landowner willingness to participate may still persist. For instance, unobserved landowner attitudes about the environment may drive the restoration participation decision as well one’s general propensity to deforest, leading to endogeneity between treatment and outcome. Anti-environmental attitudes would lead to downward bias in estimation due to being positively related to the

propensity to deforest (or to avoid restoration maintenance) and negatively related to participation in restoration activities, producing a more conservative treatment effect estimate. The fact that there is no evidence of pre-treatment differences in land use outcomes mitigates against this type of bias.

Another concern is that matching can bias difference-in-differences analysis due to “regression to the mean”¹¹. This may occur if the treated and untreated groups come from different populations. In our case, both groups come from the population of privately-owned land in the Atlantic Forest with a wide range of common land use activities. Our interviews suggest that there are networks that help facilitate enrollment in restoration, but also that these networks include all types of landowners, including those who are very skeptical of restoration. Since in this case many participants are landowners who have been convinced to participate, rather than people with a pre-existing affinity for conservation, the concerns due to regression to the mean are likely small.

Finally, there is concern that our design may violate the Stable Unit Treatment Value Assumption (SUTVA) of the counterfactual framework. SUTVA requires that there be no treatment spillovers. In our case, violation would occur if the treatment of one cell has an effect on the outcome of another cell, leading to biased and inconsistent estimation of the treatment effect. By aggregating our forest outcomes from 30m pixels to 2-hectare cells, we relax SUTVA by substantially reducing the total contiguity and fine-scale spatial dependence of treated units¹². We also reduce the potential for spillovers between treated and untreated cells by imposing a 500m buffer between treated and untreated units in the main specification, and testing for robustness of results to a 1000m buffer.

Supplementary Discussion

The Forest Code and the CAR

This section provides a brief background on the institutional landscape supporting land use change policy in Brazil, beginning with national forest legislation. In 1934, the Brazilian government established the first federal Forest Code (“Code”). The Code put forth a legal framework regulating the use and management of Brazil’s forests. The initial Code aimed to strike a balance between forest protection and Brazilian agriculture. In 1965, a major revision to the Code strengthened regulations and established key conservation tools, including Permanent Preservation Areas (APPs) and Legal Reserves (LRs). APPs and LRs require private landowners to set aside a portion of their land for conservation and to adopt more sustainable land use practices in certain areas. The location of APPs is determined by ecological features – they tend to be sited in riparian zones, on steeply sloped areas, or around lakes. Landowners have more autonomy in determining the location of their LRs.

Several updates to the legislation followed in 1989, 1996, and 2001 as well as the establishment of protected federal and state parks, biological and extractive reserves, and environmental protection areas. In 2012, a second major reform of the Forest Code, known as the Native Vegetation and Protection Law, revised and added protections, offered amnesty for past illegal activity, and created the Environmental Rural Registry (known by its Portuguese abbreviation – CAR).

The CAR continues to be a critical component of the 2012 revision because of its impact on landowner compliance with the Forest Code. The CAR is a national registry designed to increase compliance (among other goals) by mapping and monitoring rural property holdings, which are subject to environmental laws. Property owners are required to register their land with the CAR and to provide information on property boundaries and locations of APPs and LRs. In return, compliant landowners gain access to credit and rural financing programs (See Articles 29 and 41 of the Native Vegetation Protection Law).

In addition to the CAR, the new Code also established several government-led conserva-

tion programs like the Environmental Compliance Program (PRA) and added more flexibility to requirements for APPs and LRs. This included allowing some farming activities on APPs, allowing offsets for some LRs, excluding intermittent springs from APPs, and narrowing required riparian restoration buffer sizes¹³. Currently, landowners in the Atlantic Forest typically must set aside 20% of their land as Legal Reserve for preserving native vegetation, although logging and grazing are permitted on LRs as long as a state-authorized sustainable management plan is followed. In addition to revising land use policies, the new law offered amnesty to all rural landowners previously in violation of the 1965 Forest Code¹⁴. In exchange for registering with CAR, which increases monitoring and enforcement risk, landowners received amnesty for deforestation violations of the prior Forest Code.

The 2006 Atlantic Forest Law further restricts land use in the Brazilian Atlantic Forest (BAF) by making restoration legally irreversible. This law makes restoration a unique and possibly unappealing land use choice by removing the option for landowners to return restored land to pasture, agriculture, or timber in the future. However, the 2012 Forest Code included a provision (Article 81) that any land being regenerated in accordance with the 2006 law qualifies for a Legal Reserve or the environmental reserve quota (CRA) program. Under the CRA program, landowners may be compensated for restored land areas that are in excess of the minimum area required by the Forest Code. While the restored areas remain irreversible, this provision increased the appeal of restoration by putting land partially back into economic use or eligible for compensation. The restored forest in a Legal Reserve can be used to generate income under sustainable conditions, like agroforestry.

To combat forest loss and continued violations, some scholars¹³ propose strengthening and expanding rural technical assistance designed to help landowners come into compliance with the Forest Code. Authors also propose financial support and incentives to encourage better compliance. PACTO serves both of these objectives by helping landowners identify degraded land for conservation, finding low-cost restoration methods, and providing the technical assistance and initial financial support for restoration.

Theoretical framework

This section offers a conceptual framework for understanding the landowner decision to engage in forest restoration. We use a modified Von Thunen land rent framework (e.g.,^{5,15}) to help fix ideas. Private landowners are assumed to employ land at its highest economic value. That is, the land-use with the highest net benefit, conditional on land characteristics, is chosen. Land characteristics include slope, elevation, precipitation, temperature, and distance to city, each of which determines how valuable a particular use of land will be. For example, steeply-sloped land located far from a city (and thus far from agricultural markets) has a low economic value for agricultural use, as costs of cultivation and transport are increasing in slope and distance, respectively.

For simplicity, we assume landowners face two land use options: agricultural (and/or pasture) and restored forest. The benefits of agriculture are profits from harvest sold at a market. The benefits of restored forest from PACTO are avoided fines from complying with the Forest Code, but also access to credit (if registered with CAR), local forest ecosystem services (e.g., erosion mitigation and water quality), and additional income from sustainable forest products, which can be sold at market (e.g., agroforestry and non-forest timber products) or provide value for household use (e.g. firewood, building materials). The benefits of potential timber production do not apply, since the Forest Code precludes timber sales for restored forest.

Consider two privately-owned parcels, A and B , with the same characteristics. The only difference is that parcel A is much closer to a city (and thus closer to an agricultural market). The owner of parcel A chooses to use land for agriculture, which may involve clearing forest. On the other hand, the owner of parcel B experiences a high opportunity cost of choosing agriculture because transportation costs are very high. Forest has a higher net rent and is chosen instead. Supplementary Figure 5 shows land rent curves against distance to city for forest and agriculture choices. Land close to cities (more leftward) have high agricultural rent (r^a), but this decreases rapidly as distance increases. Forest rent (r^f

), on the other hand, decreases only gradually as distance increases. Starting at the origin, once a distance of I is reached, the forest rent exceeds agricultural rent, and the land use choice is switched to forest. In the range just leftward of I , PACTO targets land with low agricultural rent, providing enough increase in forest rent to induce a switch from agriculture to forest (i.e., forest restoration). This switch is depicted by parcel C , for which forest rent exceeds agricultural rent only after participating in restoration. The same logic applies to other land characteristics types, such as slope and elevation, along the horizontal axis. For participation to occur, private landowners must perceive the benefit of avoided fines, credit, and other rents to be larger than both the costs of restoration and the opportunity cost of the marginal agricultural land.

This framework suggests two main hypotheses regarding participation in restoration, with implications for our empirical strategy. First, we expect landowners with less productive land to be more likely to participate, as their opportunity costs for participation will be lower. Similarly, in areas where agricultural rents are higher due to the types of crops that can be planted, participation will be lower. These factors are a key justification for the identification strategy based on matching by land characteristics and the difference-in-differences comparisons.

Second, the institutional setting is likely to mediate impacts. Crucially, application of the Forest Code, and hence perceived benefits of avoided fines, may be higher depending upon the institutional structure of a state or municipality. If prosecution of Forest Code violations is more intensive in certain states for institutional reasons, we would expect farmers to perceive larger benefits from participating in PACTO and thereby greater rates of restoration. Graphically, these benefits (i.e., avoided legal sanction) shift the rent value of forest upward (from r^f to r^{fPACTO}), moving the indifference point left to I^{PACTO} . The way in which enforcement uncertainty influences landowner behavior and restoration outcomes can also be understood as a problem of imperfect enforcement, which asserts that the effectiveness of environmental regulations vary with enforcement quality¹⁶. It may also be the case that

some implementing organizations affiliated with PACTO are more efficient at promoting and implementing restoration—this lowers the up front cost of restoration for landholders and will therefore induce more participation. The main drivers of restoration costs include initial planting costs, sapling survival rates, continuous maintenance requirements, and soil fertility, which may also have a geographic component¹⁷. While we test for heterogeneity by distance to cities (to proxy for opportunity cost) and by state (to explore enforcement differences), we do not have sufficient information on implementing organizations for meaningful tests.

Field interview insights

To understand restoration in the specific context of the BAF, we conducted field interviews with various PACTO stakeholders in August and September of 2023. The main purpose of the interviews was to identify the key economic and institutional mechanisms that drive restoration on private land in the Brazilian Atlantic Forest. In particular, we aimed to understand why private landowners consent to restoration assistance, what characteristics make a landowner more likely to restore, and what are the necessary conditions for successful restoration. Questions for the interviews were informed by the theory presented in the previous section. Eleven individuals were interviewed, sometimes jointly, over nine separate meetings in Bahia. All interviews were conducted in-person with the exception of one government official who was interviewed by videoconference. Interviewees consisted of two government stakeholders, two NGO stakeholders, one company, two landowner consultants, and four landowners. *Landowners 1 and 4* are part of a rural settlement. Rural settlements are comprised of agricultural plots that are managed independently. They are part of the National Agrarian Reform Program and are distributed to families in vulnerable situations. They are managed by the National Institute of Colonization and Agrarian Reform (INCRA), which supports development initiatives in these areas\cite{Pereira2022}. Interviews were carried out in a semi-structured format, and interviewees were recruited using a snowball method beginning with PACTO and CI. While not necessarily representative of the total sample population in this study, these insights are valuable in linking incentive, cost, and

enforcement mechanisms of restoration to our results, theoretical framework, and broader understanding. Figure 2 shows how interviewees fit into PACTO’s organizational structure and core activities. In the sections that follow, anonymized interviewees are referred to in italics (e.g., *Government 1*).

Landowner Incentives to Restore

Three key findings emerged across all interviews: private incentives to restore are (1) primarily financial, (2) different for large and small properties, and (3) strongly mediated by how authorities enforce the Forest Code. For small landowners, enforcement was weaker, and restoration was only possible when costs could be shared with a PACTO implementer. Among large landowners (including companies), enforcement was stronger. For companies targeted by higher monitoring and financial penalties, restoration improved. Broadly, the interviews suggest that largeholders will restore if well-enforced, and smallholders will restore if financially-assisted.

Landowner Consultant 1 defined landowners’ attitude towards land use decisions and restoration: “the most painful part of the body is the pocket.” In most cases, the reason landowners restore (or not) is financial. Landowners made most land-use decisions (including restoration) by considering how it could increase financial gains or avoiding financial losses, relative to alternate choices. Importantly, landowners learned from NGOs and landowners consultants how restoration could increase net financial benefits. This information raised the economic feasibility of restoration as a competing land use. For example, a Legal Reserve of restored native vegetation can generate income from non-timber forest products and agroforestry. Restored forest also improves groundwater recharge. More water, in turn, raises agricultural yields and total income. *Landowners 2 and 3* believed strongly that “agriculture needs restoration because agriculture depends on water” and recognized that “if there’s no forest, there’s no water.” For smallholders, registering property with CAR and agreeing to a restoration plan opens access to agricultural credit and other benefits. Restoration also avoids possible financial losses due to enforcement penalties. Failing to comply with the

conservation and restoration requirements of the Forest Code can lead to substantial fines or lawsuits, mainly for large properties and companies. Interestingly, non-landowner opinions on incentives are mixed. *Government 1* believed that “if the law and fines were a major concern, we would not need [restoration assistance] programs.” *Consultant 1* believed that “the law is the biggest motivation” because of credit access and avoiding fines. In any case, whether for income, compliance, assistance, or water, the decision to restore is primarily financial.

The secondary motivation to restore was environmental. Most landowners interviewed expressed pro-environmental attitudes and reported psychological benefits from having greener spaces. One exception was *Landowner 1*, who restored exclusively for environmental benefits at the time of the interview. For this landowner, agroforestry income from the restored Legal Reserve was only providing negligible income. However, the landowner emphasized that forest restoration was an important environmental activity to pass on to future generations. And although pro-environmental attitudes are not ubiquitous, they may be associated with exposure to environmental education. *Landowners 2 and 3* expressly lamented insufficient environmental education in Brazil and suggested that “the US should invest in environmental education in Brazil because this [region] is where restoration is important.” Finally, the environmental incentive may, for some landowners, eventually come to supersede the financial incentive over time as restoration leads to noticeable improvements in local environmental quality. To this point, *Government 1* asserted that “[landowners] come for the economics and stay for the environment.”

Importantly, interviews revealed that the incentives to restore appear to be fundamentally different between largeholders and smallholders. This separation is mediated by how authorities enforce the Forest Code. Large private landowners and companies are under stricter enforcement because they influence more land, can inflict greater environmental harm, and have the money to fund restoration for Code compliance. In Bahia, government interviewees stated that strong Code enforcement by state officials induced CAR registration and better

compliance among largeholders. In states with lower enforcement, large landowners may be expected to pursue commensurately lower compliance. Smallholders in general may have minimal exposure to the Forest Code, experience less enforcement pressure, and exhibit less compliance. Landowners with very small properties (*Landowners 1 and 4*) were mostly or entirely unaware of the Forest Code prior to engaging with a PACTO implementer.

Role of the PACTO Network

The PACTO organization does not itself implement restoration but rather supports the restoration activities of existing, local restoration NGOs (i.e., “implementers”) in its network. Our interviews revealed that PACTO support has three main channels: knowledge-sharing, regional network-creation, and assistance securing funding. First, since restoration in tropical forest is ecologically complex^{18,19}, PACTO develops and disseminates science-backed restoration and monitoring protocols to its network. As *Government 2* put it, “many people do forest restoration but without knowledge.” Second, PACTO creates channels through which implementers can share restoration strategies and collaborate with one another (e.g., lectures, peer networks, and regional offices). Third, PACTO helps local NGOs raise funds and expand restoration capacity by linking them to large funding institutions. By virtue of being part of a well-organized network, local NGOs gain recognition and credibility among large, international conservation organizations. *Government 1* refers to this as PACTO “putting their stamp” on implementers. By creating this link, PACTO reduces search costs between conservation funds and effective on-the-ground implementers.

Role of Local NGOs

Most implementers are existing, local NGOs. Local NGOs are indispensable to restoration in the BAF because they have expertise in native ecological succession, and they are well-positioned to gain landowner trust. Most importantly, implementers reduce the costs landowners pay for restoration. *Landowners 1-4* stated they would not have restored without the assistance of *NGO 1*, which covered all restoration expenses and developed tailored planting and monitoring protocols. Due to the necessity of cost-sharing reported across

landowners, we expect that if funding to local NGOs were to decrease, restoration among small properties would be severely hampered.

Landowner Recruitment

Landowners are selected for restoration assistance by PACTO implementers through three mechanisms: 1) proximity to a “trust network,” 2) hydrological importance of land, and 3) the presence of unproductive (low-opportunity-cost) land. The first two criteria are mainly prerogatives of the landowner consultants and government stakeholders while the latter is explicit PACTO strategy meant to minimize landowners’ economic loss.

A trust network is an informal and expanding geographic nexus of landowners, with an implementer at the center. Landowners start working with an implementer and subsequently “vouch” for restoration to other landowners, bringing them into the network. Implementers go property-to-property to recruit landowners and have more success when word-of-mouth precedes them. *Consultant 1* emphasizes that lack of trust is a constant barrier to recruitment, saying “you have to know how to talk to them, and they have to trust you.” For this reason, effective recruiters often have an agricultural background and spend significant time earning landowner trust. The second recruitment factor, hydrological importance, involves prioritizing restoration of land that impacts high-population watersheds. This can involve government recruitment where landowners in a critical watershed are targeted first. Finally, PACTO implementers target degraded land that landowners are unlikely to use. This approach maximizes the likelihood of landowner participation by minimizing foregone agricultural income.

Restoration costs and other barriers

Interviewees emphasized that the costs of restoration are a crucial barrier to restoration. Private landowners incur restoration costs from two main sources: 1) implicit / opportunity costs (i.e., the foregone income of agriculture or pasture) and 2) explicit/direct costs, including up-front expenses and longer-term maintenance costs. Opportunity costs depend on the potential for other profitable activities and were noted to be generally lower in degraded

and abandoned areas unsuitable for agriculture or pasture. Direct costs are expenditures for materials and labor necessary for restoration, including purchasing saplings and seeds, scouting and preparing soil, planting and seeding, fencing, weeding, and monitoring.

Direct costs vary widely across restoration methods. Interestingly, the cheapest method, natural regeneration, which costs as little as \$49 per hectare, is rarely used by restoration organizations in the Brazilian Atlantic Forest^{18,20}. This may be due to its longer time commitment, less immediate results, and unforeseen direct and indirect costs²¹. Rather, the most expensive method, active restoration (e.g., tree planting), is far more common despite costing thousands of dollars per hectare¹⁸. In the Atlantic Forest, active restoration is used in over 60% of projects¹⁸ despite costing between \$700 and \$5,000 per hectare, most of which must be paid up front^{18,22}. The preference for active restoration is due to the ecological complexity of the BAF and a stronger yield of vegetation. Due to the high cost, smallholders cannot afford to restore without NGO assistance and cost-sharing.

Cash flow timing is also key to understanding the costs of restoration. Restoration is essentially a long-term investment requiring large up-front capital and delayed payoff. Asymmetrical cash flow timing can make restoration entirely infeasible in the short run, especially for smallholders. With active restoration, negative cash flows are large and up-front, followed by several years of maintenance costs. Positive cash flow are only realized years later from agroforestry, timber, or non-forest timber products, whose yield is uncertain. In the interim, landowners would experience a financial loss and need to draw on credit or savings. These future financial benefits are less certain if there are undeveloped markets for forest products or if landowners lack experience with these activities. For these reasons, restoration is often perceived as a risky land-use proposition. Previous studies indicate that unaided landowners would suffer negative cash flows for at least four years²² and possibly never recoup the full cost. Without cost-sharing from NGOs, savings, or access to credit, active restoration is not feasible for most smallholders. Even with natural regeneration, it may still make more economic sense to let degraded land lay dormant since this cheaper

method still comes with costs²¹. Largeholders are more likely to have the financial solvency to bear the costs, waiting, and uncertainty of restoration but must be well-enforced.

Our interviews corroborated the importance of cost considerations for restoration decisions among smallholders. As *NGO 2* points out, it takes four years before trees are sufficient to provide shade for agroforestry. Low-income landowners with minimal savings and less land especially cannot bridge this cash flow gap, making restoration impossible without external funding from NGOs, credit, or government restoration assistance programs. For instance, *Landowner 1* reported that agroforestry on restored land only led to marginal increases in income. Conversely, *Landowners 2 and 3*, who each own at least twice as much land, reported that agroforestry provided noticeable financial benefits and that the income from agroforestry products exceeded the costs of maintaining the restored area. Notably, these two landowners had restored forest for much longer and had entered the profitable phase of agroforestry. Nonetheless, without *NGO 1* paying for the up-front costs of restoration, these landowners likely would not have restored.

Additional challenges to restoration may include lack of technical knowledge, maintenance and protection of newly-restored areas, supply chain issues, and pests such as leaf-cutter ants. *NGOs 1 and 2* both devote substantial resources to surveying land to determine the best species and ecological succession for restoration planting. Without the technical planning and scouting stage, restoration can be highly ineffective, and landowners often lack this expertise. Second, while implementers may pay for all up-front costs of restoration, landowners are often still responsible for maintaining the restored area for several years until the trees are strong enough to withstand environmental threats. Weeding is a laborious maintenance activity that can take a low priority for landowners focused on agriculture. Potentially, the most crucial years are those between when the implementer ceases to assist and when the restored area begins to produce desired benefits of agroforestry products and water restoration. This “waiting” period produces no immediate benefits but consists of maintenance costs, possibly leading to project abandonment. Third, regional nurseries that

produce seedlings and saplings are a crucial link in the supply chain of restoration, and significant effort is devoted to collecting native seeds from surrounding land. Should seed supplies run low or nurseries lose capacity, “assisted” and “active” restoration projects would slow. Finally, leaf-cutter ants represent a long-standing ecological threat to land use activities involving vegetation, including restoration. *Company 1* specifically listed the insuppressible herbivory of leaf-cutter ants among the top five threats to forest restoration efforts.

Legal Compliance and Enforcement

Enforcement of the Forest Code drives private restoration in the BAF, but mainly for largeholders as previously discussed. Insufficient enforcement is the primary barrier to restoration among large landowners and companies. These groups have the financial capacity to pay for restoration but will only do so if state institutions proactively enforce the law. Meanwhile, smallholders are less monitored due to limited enforcement budgets. Even if enforcement increased for smallholders, restoration would still require cost-sharing and assistance from NGOs. Restoration in the BAF relies on leveraging the competitive advantage of restoration-promoting stakeholders. Enforcement agencies motivate largeholders, and NGOs motivate smallholders.

These mechanisms of restoration can be linked to our theoretical framework and Supplementary Figure 5. For large landowners, stronger enforcement shifts the agricultural rent line inward (via legal costs of non-compliance), increasing restoration. For smallholders, implementers expand the PACTO forest rent line outward by paying for direct costs of restoration that brings income and credit. Financial motivations drive restoration for largeholders and smallholders but in different ways. Largeholders restore to avoid losses from enforcement (fines and settlements), and smallholders restore to gain additional income and access to credit.

Code enforcement may be split into two focuses: 1) non-compliance with Legal Reserves and APPs and 2) environmental damages. *Government 2* explained that state environmental prosecutors and environmental agencies monitor and penalize largeholders for both

violations. But, smallholders are mainly only penalized for environmental damages, like “if they are cutting a native tree.” IBAMA enforcement agents are “always driving around” to monitor land-use but primarily to prevent acute environmental damage. The reason for treating large and small landholdings differently has to do with limited enforcement budgets, total land impact, and the landowner’s ability to pay for restoration.

Consultant 2 explained that if a smallholder “doesn’t meet the LR or APP requirement, they get a warning,” first and possibly a fine later. *Government 2* elaborated that the government knows smallholders cannot easily pay for restoration and often lack knowledge of the Code. For this reason, they receive a more lenient approach in Bahia whereby *Government 2* helps non-compliant smallholders make a plan for Legal Reserves restoration and then provides cost assistance. Large holdings are of higher interest for non-compliance because they operating large areas of the BAF, can afford restoration, and respond strongly to financial incentives. Fixed enforcement budgets are therefore more efficiently spent on largeholders who provide a higher restoration return on enforcement efforts.

Insufficient private restoration exemplifies the failure of land-use markets to provide sufficient public goods. Private incentives in the BAF under-supply native forest (the public good) because the private benefits of restoration are too low relative to agriculture, pasture, and timber. Strong enforcement is therefore required to expand forest restoration by internalizing the societal costs of deforestation to private agents. *Company 1* highlights how, on a per unit basis and in net, restoring one tree is less financially beneficial than planting one tree for timber: “Every plant you plant for production is cheaper than for restoration.” This insight encapsulates both the high opportunity cost and unappealing financial returns to restoration for private actors. Not only can restored forest crowd out timber, it generates substantially less financial proceeds than other land-uses. For example, if a eucalyptus stand rotates every six years, but native vegetation takes thirty years to provide ecosystem services or non-timber products, restoration means foregoing five timber harvests for low or uncertain future benefits. In short, forest restoration is ill-suited to the private profit motive. The lack

of private incentive to restore underscores the necessity of government enforcement. When effectively enforcing Legal Reserves and internalizing the costs of restoration to companies, which own vast swaths of land, enforcement authorities become a deciding factor for large-scale forest restoration. As such, states with substantial largeholdings and weak compliance monitoring can expect less restoration.

Notably, strong enforcement on large companies can also produce positive restoration externalities on surrounding private land. For instance, *Company 1* rents land from nearby private smallholders to produce eucalyptus. Since *Company 1* is well-monitored, it brings the rented land into Code compliance before using it. *Company 1* creates a positive externality of restoring land that would not have been restored otherwise. This occurs where enforcement is strong.

State-level enforcement appears to strongly determine restoration outcomes in the BAF if the findings in Bahia are generalizable. A key finding is that enforcement varies by the proactivity of the state-level environmental prosecutors and Ministries of Environment. In Bahia, enforcement of environmental law is particularly proactive. For instance, *Government 2* initiated a large, multi-year investigation into the Legal Reserve violations of major eucalyptus producers. The state determined that companies were growing eucalyptus in Legal Reserves instead of native vegetation. Companies settled out of court for large financial penalties. This investigation was highly proactive, including forensic satellite monitoring followed by visits to over 600 company land sites to ground-truth violations. As a direct result of the investigation and settlements, eucalyptus producers in Bahia now make earnest efforts to be in compliance with the Forest Code in order to avoid future prosecution and settlements. In short, our interviews suggested that state enforcement matters.

Variation in state enforcement may drive the state-level results reported in Figure 6. State prosecutors and other state-level environmental officials can strongly influence restoration outcomes by raising the costs of non-compliance among large landholders and raising assistance to small landholders. In our theoretical framework, a state with proactive en-

forcement would create larger benefits from participating in PACTO. For large landowners, stronger enforcement decreases the rent from agriculture (when agriculture is illegally used in the place of a Legal Reserve) in Supplementary Figure 5 by adding the costs of litigation, settlements, and fines. In states with less proactive enforcement, these costs are likely to be smaller, moving the land rent line higher and reducing the amount of land used for restoration.

Supplementary Note 1

Questions for NGOs/Government:

1. Restoration Activities

- (a) How long have you been doing restoration?
- (b) What types of restoration do you promote?
- (c) What do you think is the main reason landowners want to restore land?

2. Working with Producers

- (a) How do you find producers to do restoration? (Crucial to understand selection bias)
- (b) What types of support do you give to producers?
- (c) What benefits do producers receive when they restore? What about costs?
- (d) Can producers use restored forest to earn additional income? Why might they do this or not do this?
- (e) How many producers are you working with right now?
- (f) How long do you work with a producer? How much effort is required in year 1? The next 5 years?

3. Conservation Laws

- (a) I understand there are conservation laws in Brazil. Can you tell me about this?
- (b) How is the law enforced? Is there monitoring? Does the government give out fines?
- (c) I understand there was a new law in 2012. How did the new 2012 Forest Code impact restoration activities?
- (d) Do many producers register with CAR? If so, why?

4. PACTO-Related

- (a) When did you start working with PACTO? Did they reach out to you first?
- (b) What are the benefits of associating with PACTO?
- (c) How does PACTO support your work?
- (d) Are there things that you do now that you didn't do before you affiliated with PACTO?

5. Additional Questions

- (a) What do you think would accelerate the process of forest restoration in Brazil?
- (b) Why do you think restoration is successful in this state and not others?
- (c) What are the Legal Reserve requirements here? Does anyone use offsets?
- (d) What are your perceptions of other NGOs/GovOrgs doing restoration?
- (e) What is the history of NGOs/Gov conservation in this region?
- (f) Do producers ever stop or reduce their restoration activities? If so, why?
- (g) What do you think are the barriers to expanding your restoration efforts?

Questions for Individual Producers

- 1. What kinds of things do you produce on your land? How do you decide what to produce?
- 2. I understand you're using some land for restoration. Tell me about that. What are your general thoughts on forest restoration?
 - (a) What is your main reason for restoring?
 - (b) What other benefits do you get from having the land in restoration?
 - (c) How did you choose which land to include in the project?
 - (d) When did you start your restoration project?
- 3. Why did you decide to work with this organization (the restoration organization)?
- 4. What kinds of costs did you incur in the restoration project in the first year [probe about materials and labor, try to get approximate totals for inputs (seeds, seedlings, fencing, fertilizer, labor for planting, weeding, etc...)]?
 - (a) In subsequent years?
 - (b) Are there months in which the work is particularly intense?
- 5. (Opportunity Cost): What would you do (or did you do) with the land if (when) it was not set aside for restoration?

6. When was the last time you made a land-use change—i.e. changed the type of crops or animals you cultivate? How much land did you change (hectares)? Did you make this change by converting an existing land-use or by purchasing new land?
7. What activities were you doing on this land in the 3 years before putting it into the project?
8. How long do you think you will leave the restored land as forest?
9. If you could sell this land that you have in restoration, how much do you think you could sell it for on the market?
10. I heard that Brazil has laws about land management and conservation. We don't have that in the United States. Can you explain that to me? How does the government enforce this? What does the community think of this?
 - (a) Does the government give fines? What for?
 - (b) What things do you think cause someone to be fined?
 - (c) . If a landowner nearby received a fine, would you worry more about fines?
 - (d) What is the CAR, and what are your thoughts on registration?
 - (e) Do you have any APPs?
11. Additional Questions
 - (a) As a settlement, how do you use your land differently from private land? Restoration? Production?
 - (b) Do your land use decisions depend on what other people in the settlement are doing/growing?
 - (c) Are there ways to earn additional income from restored forest? (Ex. Agroforestry or non-timber products) Do you engage in these income-earning activities? If not, why? Do you know any landowners doing these activities? Why do some do it and others don't?
 - (d) Are you aware of PACTO?
 - (e) How does the community feel about the restoration NGO that you are working with?
 - (f) How does the community feel about restoration and the Forest Code?

Questions for Commercial Producers

1. What kinds of things do you produce on your land? How do you decide what to produce? What is your general mission?
2. I understand you're using some land for restoration. Tell me about that. What are your general thoughts on forest restoration?

- (a) What is your main reason for restoring?
 - (b) What other benefits do you get from having the land in restoration?
 - (c) How did you choose which land to include in the project?
 - (d) When did you start your restoration project?
3. Why did you decide to work with PACTO? Did they reach out to you first?
 4. What kinds of costs did you incur in the restoration project in the first year [probe about materials and labor, try to get approximate totals for inputs (seeds, seedlings, fencing, fertilizer, labor for planting, weeding, etc. . .)]?
 - (a) In subsequent years?
 - (b) Are there months in which the work is particularly intense?
 5. (Opportunity Cost): What would you do with the land if it was not set aside for restoration?
 6. When was the last time you made a land-use change—i.e. changed the type of crops or animals you cultivate? How much land did you change (hectares)? Did you make this change by converting an existing land-use or by purchasing new land?
 7. What activities were you doing on this land in the 3 years before putting it into the project?
 8. How long do you think you will leave the restored land as forest?
 9. If you could sell this land that you have in restoration, how much do you think you could sell it for on the market?
 10. I heard that Brazil has laws about land management and conservation. We don't have that in the United States. Can you explain that to me? How does the government enforce this?
 - (a) Does the government give fines? What for?
 - (b) What things do you think cause someone to be fined?
 - (c) If a landowner nearby received a fine, would you worry more about fines?
 - (d) What are the Legal Reserve requirements? I hear it is possible to use offsets.
 - (e) What is the CAR, and what are your thoughts on registration?
 - (f) Do you have any APPs?
 11. How is restoration in this state different from other states?
 12. Do you have plans to expand? What other goals does the company hope to achieve?

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