

Holding Ground: The Resilience of Protected Areas during Institutional Weakening

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Protected areas are a cornerstone of global conservation policy, yet those located in remote regions are often viewed as inefficient because they protect forests under little immediate threat. This view assumes static institutions and stable land-use patterns. We show instead that the conservation value of protected areas is dynamic and can rise sharply when environmental governance weakens and deforestation pressure expands. Studying Brazil’s Amazon rainforest during two major institutional shocks—the 2012 Forest Code reform and the 2019–2022 Bolsonaro administration—we find that protected areas prevented large increases in deforestation during periods of institutional decline. Using quasi-experimental evidence from 2004 to 2022, we show that deforestation surged outside protected areas but remained stable within them, particularly in remote regions. Areas previously considered non-additional thus revealed a latent conservation value, functioning as critical buffers against governance erosion. These findings have important implications for global conservation strategies and 30×30 commitments.

Protected areas (PAs) are the cornerstone of global conservation policy, covering more than 17% of the world’s terrestrial surface (1). A central debate concerns whether PAs located in remote, sparsely populated regions have real conservation value, with critics arguing that these areas protect forests facing little immediate pressure (2,3,4). While extensive evidence shows that PAs reduce deforestation on average (5,6,7,8,9,10,11,12,13,14,15,16,17,18), most studies implicitly assume PA effectiveness is constant over time and across space, even as political and enforcement conditions change. We argue that this perspective masks a dynamic dimension of conservation: remote PAs can hold a “latent conservation value” that becomes visible only when governance weakens and deforestation frontiers expand. This option value (19), the insurance provided against future governance shocks, is difficult to observe under stable conditions but becomes starkly visible during periods of institutional decline. A proper assessment of the effective conservation value of remote PAs requires considering both temporal changes in institutional capacity and the spatial expansion of deforestation.

For critical ecosystems nearing tipping points like the Amazon rainforest (20,21,22), understanding this dynamic dimension is not merely academic but urgent. Using Brazil’s Legal Amazon¹ as a setting characterized by sharp political shifts, we test the prediction that protected areas increase their relative effectiveness precisely when national institutions weaken. We focus on two major governance shocks: the 2012 Forest Code reform, which granted amnesties for illegal deforestation and reduced restoration requirements, and the Bolsonaro presidency (2019–2022), which dismantled enforcement structures and slashed environmental budgets.

Leveraging satellite data and a difference-in-discontinuities design comparing forest loss just inside versus just outside protected area boundaries before and after major institutional shocks, we show that protected areas became relatively more effective as environmental governance eroded. The largest gains occurred in protected areas located in remote frontier regions, where deforestation accelerated sharply outside protected area boundaries while remaining stable inside. These patterns reveal the latent conservation value of protected areas: lands that appear marginal under strong

¹The Brazilian Legal Amazon (Amazônia Legal) is a federal planning region comprising the states of Acre, Amapá, Amazonas, Pará, Rondônia, Roraima, Tocantins, Mato Grosso, and the portion of Maranhão west of 44°W (about 5.0 million km², roughly 59% of Brazil). It spans three biomes: the Amazon biome (entirely within the region), substantial portions of the Cerrado, and a small portion of the Pantanal in southwestern Mato Grosso.

governance can become critical buffers when institutions weaken and deforestation frontiers expand, with important implications for global conservation strategies and 30×30 commitments.

1 Institutional Context and Deforestation in Brazil

Protected areas constitute a centerpiece of governance efforts to reduce or limit deforestation in the Brazilian Amazon. These areas comprise legally distinct categories that vary in their management and land-use restrictions which together cover over 40% of the Legal Amazon: (i) Indigenous Territories (ITs)² recognize collective land rights of Indigenous peoples and grant exclusive use and management rights, (ii) Strictly Protected Areas (SPs), such as national parks and biological reserves, prohibit extractive activities and the presence of local communities, and (iii) Sustainable Use Areas (SUs), including extractive reserves, allow limited economic activity under conservation-oriented management plans³

The forests governed by these protected areas underpin both national development and global environmental stability, sustaining water cycling for agricultural productivity (24) and providing crucial ecosystem services for local communities and Indigenous peoples. The Amazon rainforest further stores vast amounts of carbon essential for stabilizing the global climate (25,26) and harbors high levels of biodiversity (27). These multiple functions place Brazil’s forests — and, crucially, the protected areas that govern large portions of them—at the center of a persistent conflict between economic development and conservation goals. These tensions intensified in the early 2000s, when historically high deforestation rates prompted the federal government to launch the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm) in 2004 (28).

The first phase of the program (PPCDAm I, 2004–2008) introduced an unprecedented, coordinated federal strategy combining strengthened command-and-control enforcement, rapid improvements in satellite-based monitoring, and targeted credit restrictions, while the second phase (PPCDAm II, 2009–2012) consolidated and expanded these measures through deeper inter-agency coordination. The program proved highly successful: national deforestation fell by 76%, and pro-

²Indigenous Territories are not always classified as protected areas in formal conservation typologies, as they are governed through collective property rights rather than state management. We include them because they function as de facto protected areas and consistently outperform state-managed reserves in preventing deforestation (16,23).

³We refer the reader to the Supplementary Text for more information on the different types of Protected Areas.

tected areas retained or even increased their effectiveness (29, 30). Prior studies, such as Nolte et al. (2013) (7), show that during this period of strong enforcement, protected areas consistently reduced deforestation relative to unprotected areas, with Indigenous Territories avoiding the greatest aggregate forest loss; however, evidence on how these effects evolve under subsequent institutional rollback remains limited. Below, we outline the two institutional breaks that structure our analysis.

1.1 The 2012 Forest Code Reform

The first break in this enforcement framework came with the Forest Code reform in 2012. The very success of command-and-control enforcement in limiting deforestation generated strong political backlash from rural agricultural interests, whose legislative power expanded sharply after 2011 (28). The new Forest Code granted amnesty for pre-2008 illegal deforestation, reduced legal reserve requirements, and weakened enforcement mechanisms, especially in frontier regions (31, 32, 33). These changes reversed key elements of the earlier PPCDAm framework and opened space for renewed expansion of the deforestation frontier by relaxing the responsibility and liability of illegal deforesters. This first break formalized the beginning of the process of environmental institutional weakening in Brazil by creating a sense of impunity for illegal deforestation (34, 28).

1.2 The Bolsonaro Administration (2019–2022)

A second break occurred after the election of Jair Bolsonaro in 2018. His administration dismantled enforcement structures (see Tables S1, S2, and S3 for a description of legislative changes), cut the budgets of enforcement agencies (see Tables S6 and S7 for budget changes), and sidelined monitoring systems, leading to unprecedented levels of deforestation (30, 35, 36). The protection of Indigenous peoples and their territories, previously under the National Indian Foundation (FUNAI), was transferred to the Ministry of Agriculture, and bills proposing to open these territories up for mining, agriculture, and dams accelerated in the legislature (37). The Chico Mendes Institute for Biodiversity Conservation (ICMBIO), charged with the management of sustainable use and strictly protected areas, lost 26% of its budget in 2019, and its subnational presence was reduced through staffing changes and the removal of enforcement units (38). These processes of environmental institutional weakening also shaped individual behavior by increasing feelings of impunity,

thereby increasing illegal deforestation, land invasions, and violence against environmentalists and Indigenous communities (39, 28, 40).

1.3 Deforestation Patterns

Figure 1 illustrates how deforestation dynamics evolved over this period (2004–2022) across conserved and non-conserved lands in both the Arc and non-Arc of deforestation.⁴ Distinguishing between Arc and non-Arc regions is critical for evaluating the conservation value of PAs over time, particularly in remote regions, as it reveals their effectiveness when deforestation spreads into previously low-pressure frontier regions. Throughout the paper, we measure deforestation as the loss of primary (old-growth) forest, identified using 1985 as a baseline and tracked at 30-meter resolution using Mapbiomas Collection 9 (41), with pixels aggregated at the grid-cell level.⁵

In the Arc, non-conserved areas exhibited the highest deforestation rates, peaking in the early 2000s before falling sharply with the implementation of PPCDAm. This decline leveled off after 2012 and reversed following Bolsonaro’s election, with non-conserved deforestation rates rising above 1.0% by the early 2020s. By contrast, ITs, SPs, and SUs maintained consistently low rates throughout, with only modest increases during periods of institutional weakening. In non-Arc regions, deforestation rates were lower overall, but the same institutional breaks are visible: non-conserved areas experienced renewed increases after 2012 and again post-2018, while protected areas remained comparatively stable. The widening post-2012 gap between conserved and non-conserved lands suggests that PAs continue to provide protection despite weakened national enforcement, highlighting their latent conservation value. Indigenous Territories, in particular, showed the most stable protection across both regions.

Figure 2 maps this deforestation pattern across three geographic zones in the Arc and Non-Arc of Deforestation, highlighting changes before and after the 2012 Code Reform and Bolsonaro’s

⁴The Arc of Deforestation refers to the crescent-shaped frontier of agricultural expansion running along the southern and eastern edges of the Brazilian Amazon. It includes municipalities in the states of Acre, Mato Grosso, Pará, and Rondônia that have historically experienced high deforestation pressure. Non-Arc regions comprise the remaining states of the Legal Amazon that historically experienced lower deforestation pressure, including municipalities in Amazonas, Roraima, Amapá, Tocantins, and Maranhão.

⁵See Data section of Supplementary Materials for details.

election. Zone A (northern Amazon, non-Arc) illustrates how frontier expansion reached remote areas only after 2012, with PAs serving as bulwarks. Zone B (Arc of Deforestation) shows persistent high pressure but continued buffering effects of PAs. Zone C (western Amazon, non-Arc) documents frontier advance into previously undisturbed landscapes after 2018, again with PAs limiting incursions. Across zones, the evidence supports the argument that the relative value of PAs increases during institutional weakening—not because internal management improved, but because external pressures intensified (a point to which we return later).⁶

2 Results

We now turn to a causal analysis of the patterns described above, proceeding in three sequential steps. We begin by estimating the causal effect of protection using a geographic regression discontinuity (RDD) at PA boundaries. This design addresses the challenge that protected areas are often located in more remote regions facing lower baseline deforestation pressure (42, 43, I3), by comparing pixels immediately outside PA borders to those just inside (I6, I7). We then extend this framework with a difference-in-discontinuity design that exploits key moments of institutional weakening to test how conservation effectiveness evolves over time. This approach combines spatial variation at PA boundaries with temporal breaks in environmental institutions, allowing us to isolate how protection effectiveness responds to governance decline and to compare heterogeneous responses across protected area types and regions. Finally, we complement these estimates with spatial evidence examining whether dynamic effects are driven by changes inside or outside protected area boundaries, distinguishing whether growing relative effectiveness reflects improvements in internal management or the encroachment of deforestation frontiers into surrounding lands while PAs maintain their protective role.

2.1 Geographic Regression Discontinuity Estimates

Figure 3 presents RDD estimates for the full sample and separately for the Arc of Deforestation and non-Arc regions, using a 12km buffer around protected areas. We examine effects across

⁶Across zones, new protected areas emerge over time. Figure S8 shows the cumulative number of ITs, SPs, and SUs designated over time.

four periods: before the 2012 Forest Code reform (2004–2007 and 2007–2011), after the reform (2012–2018), and the Bolsonaro administration (2019–2022). Details on the RDD specification and assumptions are provided in the research design section. We report balance checks in Tables S14, S15 and S16, sensitivity analyses in Tables S11, S12, and S13, and placebo tests in Table S17. Finally, we present yearly RDD estimates in the supplementary appendix (Tables S8, S9, S10, and S11).

2.1.1 Indigenous Territories

For ITs, the estimated coefficients reported in Table S7 are negative and statistically significant across 2004–2022, suggesting a robust protective effect against deforestation. The magnitude of this effect, however, varies over time: it starts in the first period (2004–2007) with a reduction of 0.81 percentage points (pp), declines in the years leading up to the 2012 Forest Code reform, and partially rebounds thereafter. After 2018, under the Bolsonaro administration, the estimates increased again, reaching -0.49 pp. Across all periods, ITs have been more effective inside the Arc of Deforestation, while protection in non-Arc areas has strengthened over time, particularly following the Forest Code reform and during the Bolsonaro administration (see the Non-Arc column in Table S7 for coefficients).

2.1.2 Strictly Protected Areas

Figure 3 indicates that SPs had little effect during 2004–2007 but began to exhibit a clear impact from 2007 onward, increasing their effectiveness through 2022 (see Table S7 for the full set of coefficients). The effect follows a steady upward trajectory, with deforestation reductions increasing over time and reaching a peak of approximately -0.88 pp under the Bolsonaro administration. Figure 3 indicates that this peak is also driven by protection extending beyond the Arc of Deforestation, representing the first time in our series that SPs show significant effects in non-Arc areas (see Table S7 for detailed coefficients).

2.1.3 Sustainable Use Areas

SUs follow a trajectory similar to SPs. Although the protective effects were significant before the Forest Code reform, they gained greater relevance in absolute terms afterward, as shown in Figure 3). The peak occurs under the Bolsonaro administration, when SUs more than tripled the effect observed during the Forest Code period, achieving a reduction of 0.9 pp (see Table S7 for coefficients). Geographically, SU effects were initially concentrated within the Arc of Deforestation, but following the 2012 Forest Code reform, their influence expanded into non-arc areas. This pattern suggests that post-2012, SUs not only became more effective but also extended their protective impact beyond the arc, sustaining forest protection even under adverse institutional conditions.

2.2 Dynamic Conservation Effects Under Institutional Stress

The geographic RDDs show that following the institutional shocks in 2012 and 2018, the average effectiveness of PAs against deforestation increased relatively, with Non-arc regions becoming more effective. While suggestive, the RDDs do not formally assess the effects of institutional breaks on deforestation. To address this, we employ a difference-in-discontinuities approach (44) that combines spatial discontinuities at PA boundaries with temporal breaks in environmental institutions. This framework estimates how protection effectiveness at boundaries varies before and after major episodes of institutional weakening, isolating the impact of governance decline from broader deforestation trends. The research design section describes the difference-in-discontinuity specification and its identification assumptions.

Figure 4) presents the main results, decomposing the total impact at protected area boundaries. Our coefficient of interest is the *Inside* \times *Post* interaction, which captures the additional change in protection following the 2012 Forest Code reform and the 2019-2022 Bolsonaro Administration. The exact coefficients and standard errors are reported in Appendix Tables S12 and S13. We also present the total effect (the sum of the persistent pre-reform *Inside* coefficient and the *Inside* \times *Post* interaction) to show the overall magnitude of protection at PA boundaries after the reform (Appendix Table S14). This decomposition allows readers to distinguish between baseline protection levels before institutional weakening and the specific impact of institutional changes on the protective effects of PAs.

2.2.1 Indigenous Territories

Figure 4 shows that ITs maintained strong and stable protection throughout the study period. In the full sample, the baseline pre-2012 effect corresponds to a 0.35 (pp) reduction in deforestation relative to surrounding areas. Including the incremental effect after 2012, the total protective impact rises to roughly 0.41 pp and reaches 0.50 pp by the post-2018 period. Disaggregating by region, ITs inside the Arc had large baseline protective effects of about 0.60 pp, rising to 0.66 pp post-2012 and 0.80 pp post-2018. Outside the Arc, baseline effects were smaller (0.11 pp) but increased substantially after 2012, reaching 0.21 pp post-2012 and 0.26 pp post-2018. Thus, while ITs were consistently effective everywhere, the relative gains post-reform were strongest in remote, Non-Arc regions where baseline protection was more modest (see Tables S12, S13, and S14, Panel A, for the reported coefficients).

2.2.2 Strictly Protected Areas

Contrary to ITs, which remain mostly as effective pre and post institutional shifts, the center column of Figure 4 demonstrates a marked strengthening of SP effectiveness after institutional weakening. In the full sample, baseline protection was 0.24 pp pre-2012. This was more than doubled by the additional post-2012 gain, bringing the total effect to 0.54 pp, and by 2018, SPs reduced deforestation by 0.83 pp relative to adjacent non-conserved lands. Within the Arc, SPs were already strong, with a baseline effect of 0.41 pp that increased to 0.63 pp post-2012 and 0.78 pp post-2018. But the most striking improvements occurred outside the Arc: baseline protection there was negligible (0.07 pp), yet by post-2012 the effect rose to 0.45 pp and further to 0.84 pp post-2018. These results indicate that SPs in remote areas, once less consequential, became critical as deforestation pressures expanded beyond traditional frontiers (see Tables S12, S13, and S14, Panel B, for the reported coefficients).

2.2.3 Sustainable Use Areas

The right column of Figure 4 highlights the most dramatic increase in effects, which are observed for SUs. Before 2012, SUs had relatively modest effects, with baseline protection of 0.18 pp in the full sample. After the 2012 reform, the incremental gain was more than twice as large as the

baseline, lifting the total effect to 0.60 pp, and by post-2018, SUs achieved reductions exceeding 1.0 pp. Within the Arc, baseline SU protection was about 0.26 pp, growing to 0.60 pp post-2012 and 0.96 pp post-2018. But again, the largest changes were in Non-Arc regions: baseline protection was only 0.06 pp, yet increased to 0.59 pp post-2012 and 1.1 pp post-2018 (see Tables [S12](#), [S13](#), and [S14](#), Panel C, for the reported coefficients). These results suggest that SUs became relatively more efficient as institutional capacity declined.

2.3 Are Dynamic Effects Driven by Encroachment of the Deforestation Frontier?

The RDD and difference-in-discontinuity results show that PAs become relatively more effective as institutions weaken, but cannot distinguish whether this reflects changes inside or outside PA boundaries. To disentangle these mechanisms, we analyze how deforestation discontinuities evolve on either side of borders. If driven by lower deforestation inside PAs, this would imply improvements in internal management or local enforcement. If driven by higher deforestation outside while rates inside remain stable, this would indicate that borders continue as strong barriers even as external pressures intensify. [Figure 5](#) supports the latter interpretation. Each panel plots average deforestation rates (y-axis) by distance from the conservation unit boundary (x-axis), where the cut-off at 0 represents the boundary itself. Negative values on the x-axis correspond to land just outside the protected area, while positive values represent land just inside. A visible drop at the boundary (i.e. a discontinuity) indicates a sharp decline in deforestation moving from non-protected to protected land, and thus reflects effective conservation enforcement. Blue lines represent pre-reform years (2004–2011), with lighter shades corresponding to earlier years and darker shades to later years within that period. Red lines represent the post-2012 period, with lighter shades indicating earlier post-reform years and darker reds for more recent years.

Following the 2012 reform, and especially during the Bolsonaro administration (2019-2022), deforestation rates just outside protected area boundaries increased markedly in Non-Arc regions, while deforestation inside remained low and stable. This is particularly evident in the bottom-right panels for SPs and SUs, where post-2012 (red) lines show a sharp vertical gap at the boundary which was absent in the pre-2012 period. The widening discontinuity provides visual confirmation

of the growing relative effectiveness of protected areas in remote regions, driven by rapidly rising clearing outside PAs while internal clearing remains stable.

3 Discussion

This paper shows that the conservation value of protected areas is not fixed but strongly shaped by institutional context (43 3). When national environmental governance weakened, protected areas across Brazil’s Amazon became substantially more effective at limiting deforestation. While Indigenous Territories consistently reduced forest loss in all periods, the largest increases in protection came from Strictly Protected and Sustainable Use areas located in historically low-pressure regions. In these areas, conservation effectiveness more than doubled after the 2012 Forest Code reform, precisely as enforcement capacity declined and frontier expansion accelerated. Remote PAs often viewed as non-additional under static evaluation criteria (43 3) became highly consequential as pressures shifted into new regions. Most post-reform increases in effectiveness were concentrated in Non-Arc municipalities, where deforestation surged just outside PA boundaries while remaining low and stable inside. This pattern illustrates the “latent conservation value” of PAs: areas that seem marginal under strong governance can become critical bulwarks when institutions weaken.

These results provide nuance to the dominant expectation that weaker institutional enforcement necessarily undermines PA effectiveness (45, 46, 7, 47). Our results suggest that PAs become more effective relative to their surroundings under institutional weakening, not because internal enforcement improves, but because external conditions deteriorate more rapidly outside their borders. This builds on work by Nolte et al. (2013) (7), who examined PA effectiveness during Brazil’s period of strengthening environmental governance under PPCDAm (2004–2012). Their study showed that PA effectiveness remained constant as national institutions improved, suggesting PAs were already operating at high capacity. Our analysis complements this earlier work by examining the reverse institutional trajectory after 2012, revealing asymmetric dynamics: while PAs did not gain additional effectiveness when institutions strengthened, they increased their relative effectiveness when institutions weakened. Moreover, our spatial disaggregation uncovers substantial heterogeneity masked in prior aggregate analyses: the increases in relative effectiveness were concentrated in previously remote, Non-Arc regions where PAs were often considered non-additional.

Our findings also reframe debates on PADDD (Protected Area Downgrading, Downsizing, and Degazettement) and “paper parks”. PADDD research has emphasized de jure changes that reduce protection (46, 48, 49, 50, 51), while work on paper parks has concluded that PAs in weak-capacity states are largely ineffective (18, 52). By contrast, we show that even when national institutions weaken without formal boundary changes, PAs can retain and even expand their relative protective role. This highlights the need to distinguish between formal downgrading and de facto erosion of state capacity, and to recognize that PAs may act as institutional anchors during times of volatility.

Several important caveats must be emphasized. First, our findings should not be interpreted as evidence that defunding environmental institutions is inconsequential. The resilience we document likely reflects extraordinary efforts by Indigenous communities to defend their lands in the face of escalating threats, often at great personal cost (53, 54, 55, 56, 39, 40). Second, our analysis examines a relatively short period of institutional weakening (2012–2022), with the most severe phase from 2019–2022. PAs may function as short-term buffers against governance shocks, but it remains unclear whether this resilience would persist under sustained institutional erosion. Third, our empirical strategy identifies local average treatment effects at protected-area boundaries. This design enables credible causal inference, but the resulting estimates are most informative about marginal forest near borders and may not generalize to protected-area interiors or regions far from PA borders. Fourth, leakage remains a concern: deforestation displaced from protected areas may be reallocated to nearby unprotected land. Our focus on before–after dynamics of already-established protected areas, together with direct evidence that post-shock changes are driven by rising deforestation outside protected areas, somewhat mitigates this concern, and existing evidence for Brazil suggests that leakage from protected areas is limited (57), yet spatial spillovers remain a potential source of bias. Finally, while PA boundaries held during our study period, this does not imply that environmental governance is dispensable. We show resilient effects during a relatively short period of institutional weakening. However, longer term institutional decline might lead to very different land-use dynamics.

Altogether, our results suggest that the designation of protected areas in remote frontier regions can be politically feasible and economically efficient once their latent conservation value is taken into account.⁷ Remote protected areas that proved most consequential during periods of institutional

⁷The Supplementary Text presents an illustrative cost-benefit analysis comparing the private returns to land con-

weakening were established on public forests with few competing claims, keeping designation costs and political resistance low. Although these areas appeared marginal under static evaluations, the private profits foregone by protection in such regions are small (58) relative to the social costs of forest loss. Avoiding conversion of intact Amazon forest prevents emissions equivalent to hundreds of tons of CO₂ per hectare (59, 60), dwarfing the returns to extensive land uses feasible in remote locations. By securing these lands at low ex ante cost, remote protected areas functioned as institutional insurance, becoming critical buffers precisely when governance weakened and deforestation pressure expanded.

Thus, conservation strategies should not be evaluated solely on immediate additionality, but also for their latent conservation value under uncertain political futures. What may appear non-additional today can become tomorrow's most critical line of defense during governance shocks. In contexts of rising political volatility, integrating institutional resilience, latent conservation value, and political feasibility into conservation planning is therefore essential.

version in remote frontier regions to the social benefits of avoided carbon emissions from intact forest.

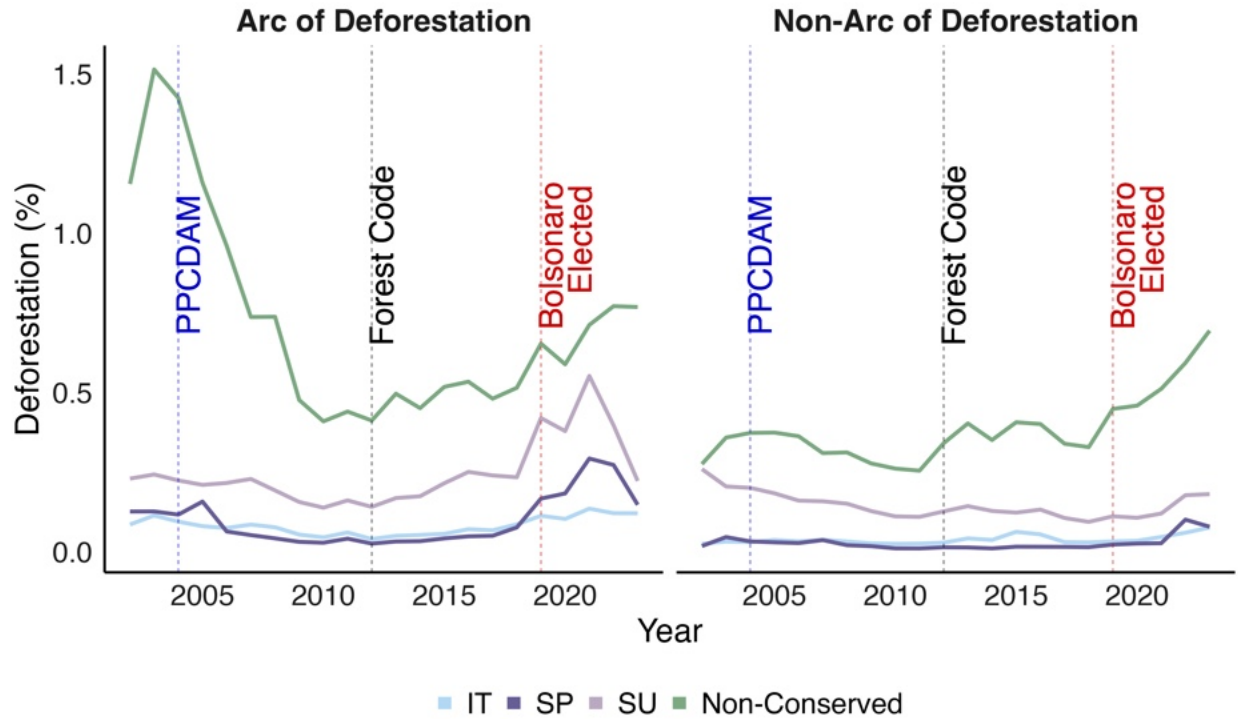


Figure 1: Annual deforestation rates (%) in conserved and non-conserved lands across the Brazilian Amazon, 2002–2022. The left panel shows areas within the historical Arc of Deforestation, while the right panel shows Non-Arc regions. Vertical lines mark three key institutional shifts: the introduction of PPCDAm in 2004, the 2012 Forest Code reform, and the 2018 election of President Bolsonaro. Protected areas (ITs, SPs, and SUs) exhibit consistently low deforestation rates, while non-conserved lands display sharp declines under PPCDAm, followed by renewed increases after 2012 and 2018, underscoring the role of PAs as buffers against governance weakening.

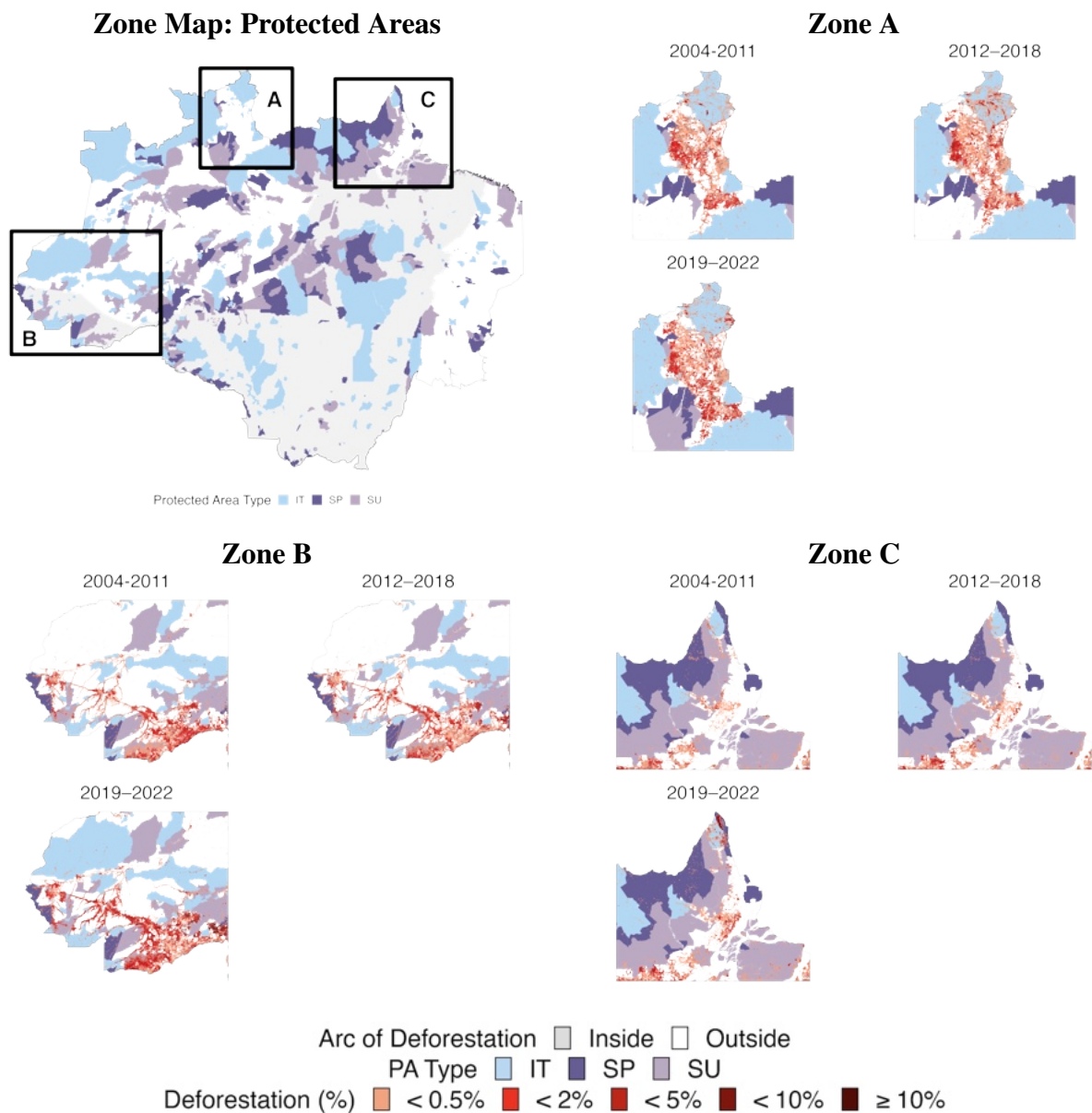


Figure 2: The figure illustrates average deforestation across Zones A, B, and C in relation to Protected Area boundaries. Zone A, located in the states of Amazonas, Roraima, and Pará, encompasses over 21 municipalities and 50 protected areas. Zone B, covering the states of Roraima, Acre, and Amazonas, includes more than 44 municipalities and 92 protected areas. Zone C, situated in the states of Pará and Amapá, contains over 48 municipalities and 39 protected areas.

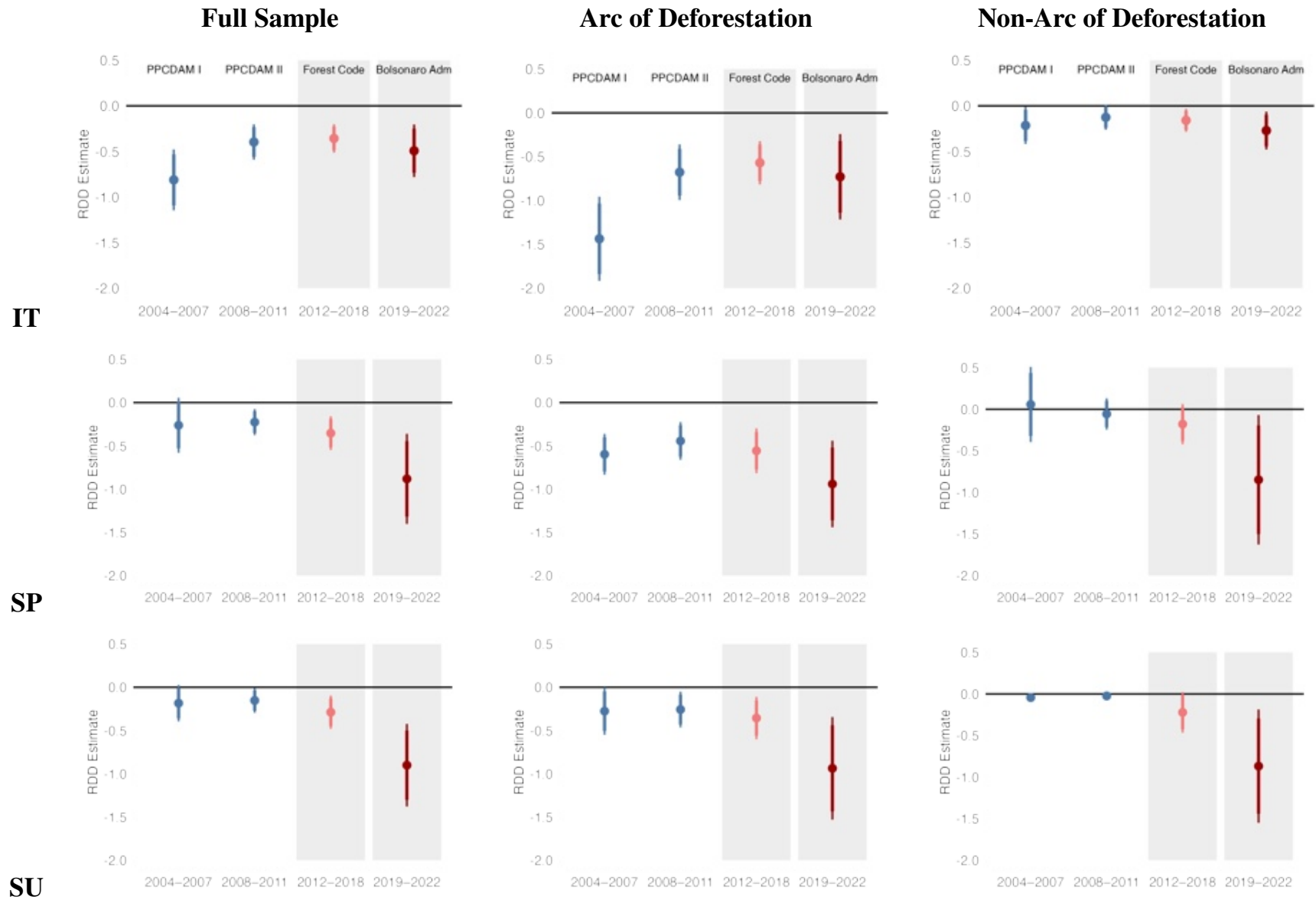


Figure 3: RDD estimates for IT, SP, and SU (rows), showing period coefficients for the Full Sample, Arc, and Non-Arc of Deforestation (columns) using a 12km bandwidth. The periods correspond to 2004–2007 (PPCDAM I), 2008–2011 (PPCDAM II), 2012–2018 (Forest Code), and 2019–2022 (Bolsonaro Adm.)

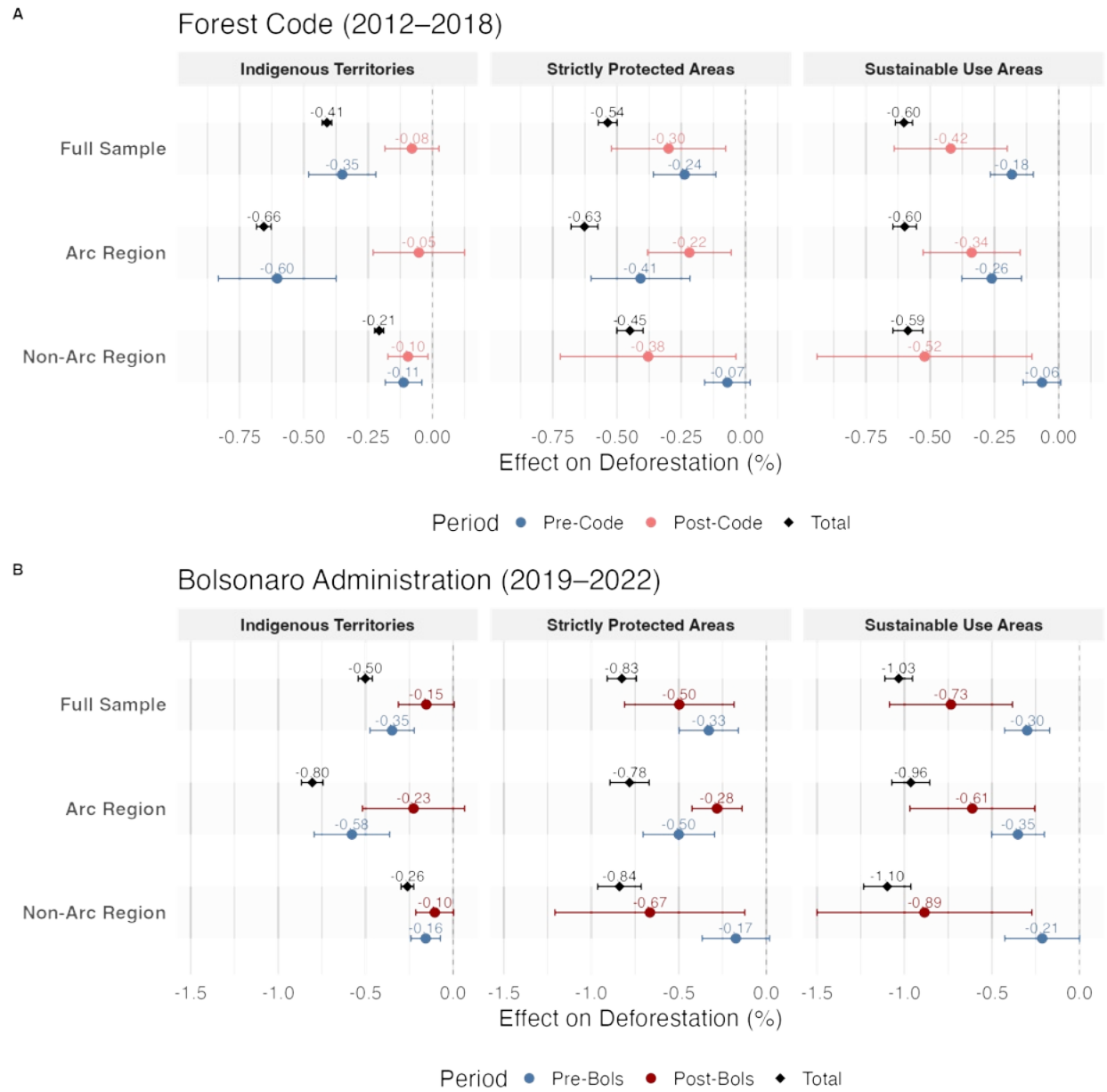


Figure 4: This figure presents a decomposition of effects from difference-in-discontinuities regressions, where the dependent variable is the percentage change in deforestation. Coefficients are drawn from Tables [S12](#) and [S13](#) and are estimated using equation [S2](#). Results are reported for Indigenous Territories, Strictly Protected Areas, and Sustainable Use Areas, and are shown separately for the full sample, municipalities inside the Arc of Deforestation, and those outside it. Blue coefficients represent boundary effects under the pre-2012 Forest Code, while red coefficients capture additional effects following the 2012 Forest Code reform and during the Bolsonaro administration. The black coefficient denotes the total effect, combining pre- and post-period estimates. Panel A focuses on the post-Forest Code period, and Panel B on the Bolsonaro administration.

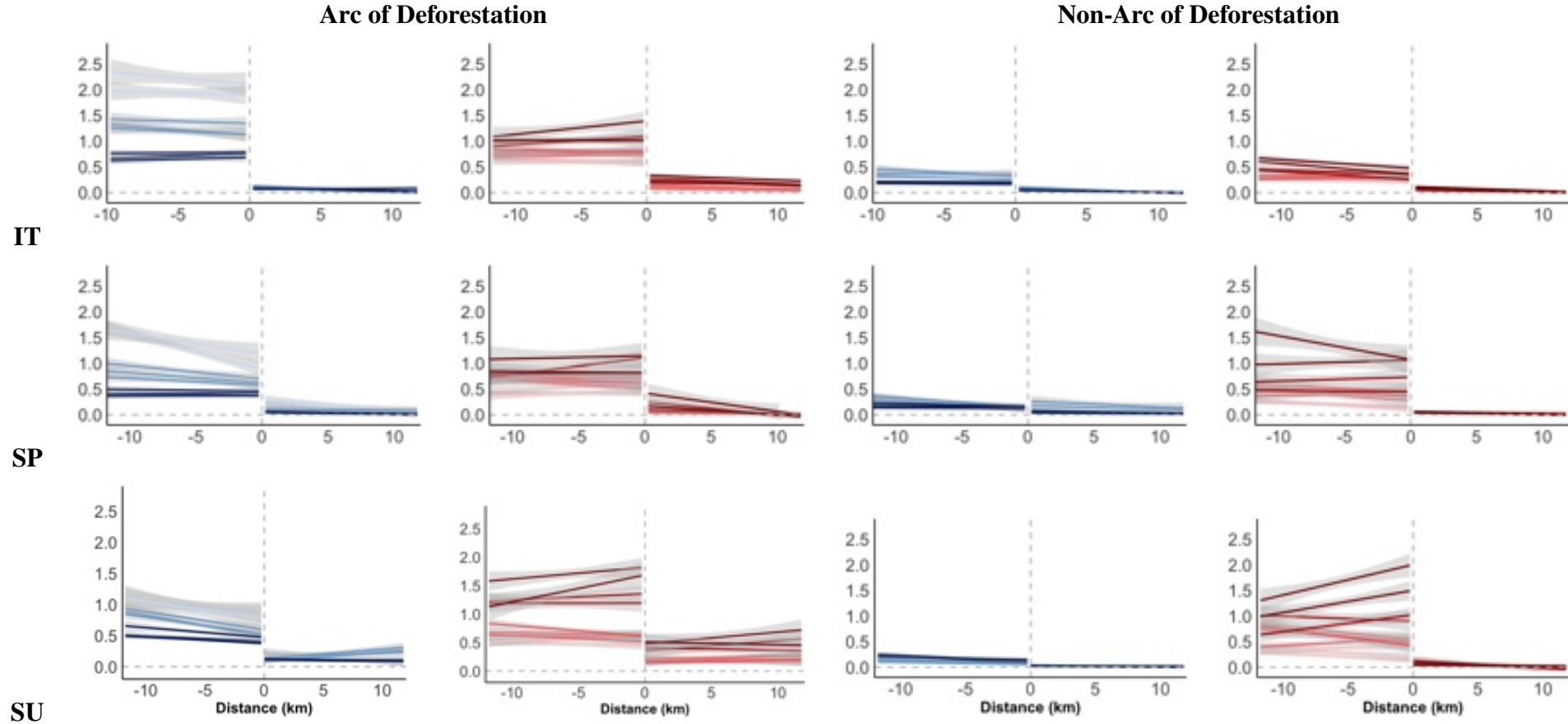


Figure 5: RDD plots by PA category and deforestation region (12km bandwidth). Columns show Arc vs. Non-Arc and pre-2012 vs. post-2012 periods; rows show IT, SP, and SU. Blue lines indicate 2004–2011, red lines 2012–2022, comparing areas inside and outside conservation units.

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Supplementary materials

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Supplementary Materials for

Holding Ground: The Resilience of Protected Areas during

Institutional Weakening

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Materials and Methods

Data

Our unit of analysis is a 4km² square (2km x 2km) which we generate as a grid over the Brazilian Legal Amazon from 2004 to 2022. We believe the size of these grid-cells is adequate for our study as it closely follows past analyses (16, 61) but is slightly smaller allowing us to capture finer grain changes and dynamics over time. Figure S5 demonstrates the creation of our grid sample. Our sample includes grids that are within 12km of a protected area's border, on either side of it – as shown in S1. We obtain the geolocation of Sustainable Use Areas and Strictly Protected Areas from the Ministry of the Environment (62) which provides their geographic location, the year they were recognized, and whether they are strictly protected or sustainable use. The Indigenous Territory shapefile is provided by the Ministry of Indigenous Peoples (63), we update the year an Indigenous Territory gains its full property rights from the *Instituto Socioambiental* (64). We measure the distance of each grid (in km) to the cut-off, defined as the border of a CU. Treated units inside PAs have a positive distance to the discontinuity, while control units have negative values. Figure S2 maps protected areas by category across the Brazilian Legal Amazon and S3 differentiates between control and treated units around these protected areas.

To measure yearly deforestation rates in our sample, we use data from Mapbiomas Collection 9 (41). As Mapbiomas provides forest balance data which does not distinguish between primary forest cover and secondary forest cover, we follow strategies outlined in the literature in creating our deforestation measure (65, 66). Using the forest formation class, we identify old-growth forest using 1985 as a baseline year, at a spatial resolution of 30 meters. When a pixel gets cleared in a given year, it remains cleared for the rest of our sample and takes on the value of 1. This allows us to strictly measure the clearing of primary forests, leaving out dynamics in secondary forests. We aggregate the value of pixels at the grid level and compute the share of pixels deforested in each grid. Our final outcome measures the share of pixels within a grid that were primary forest in 1985 and cleared in year t .

To provide evidence of balance across our treated and control units we compute the distance of each grid to the nearest city (67), the nearest river (68), and the nearest road (69). We also calculate the average elevation, hillshade, and slope for each grid obtained from the Global Multi-resolution

Terrain Elevation Data (GMTED2010) by USGS (70). Distance variables help account for the costs of transportation and access to markets while grid characteristics control for key geographic conditions that increase (or decrease) the chances of deforestation (71).

We take several steps to ensure our sample of treated and control forested grids is appropriate for comparison. First, we remove grids with less than 30% forest cover in 1985 to ensure we are strictly analysing forested pixels. Second, we delete grids (i) that intersect protected area borders to ensure grids are entirely on either side of a border and (ii) that are within 20km of Brazil's territorial border to avoid confounding effects linked to external factors. Finally, as some protected areas overlap or share borders with each other, we risk to compare treated units in Indigenous Territories to treated units in Strictly Protected Areas or Sustainable Use Areas. To avoid this, we transform our protected area polygons into lines and delete lines which have less than 30% control units as well less than 30% treated units. Figure S4 identifies the control and treated units that make up our final sample between 2004 and 2022. The final dataset has 1,563,754 observations, descriptive statistics by protected area type are available in tables S4, S6, and S5.

Research Design

Geographical Regression Discontinuity Design

We follow the design proposed by (16) to estimate whether the weakening of environmental institutions after 2012 (2018) affected PAs' ability to prevent deforestation. This design leverages PAs' (IT, SP, and SU) boundaries to estimate local treatment effects (LATE) through a geographic regression discontinuity (RDD). Specifically, we compare observations within a 12km buffer on either side of homologated PAs' borders, ensuring that the land plots analyzed are plausibly similar, except for their designation as inside or outside a protected area. This design helps to ensure that the estimated effects capture the impact of homologation, rather than spurious spatial correlations.

The differential effects of PAs on deforestation are estimated using the following regression model:

$$Def_i = \alpha + \tau T_i + \beta_1 f(X_i - c) + \epsilon_i \quad (S1)$$

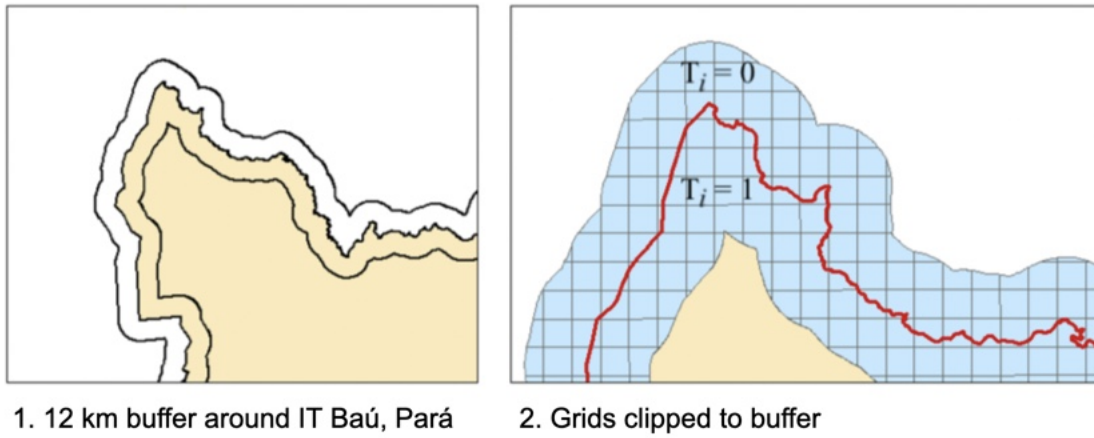


Figure S1: Regression Discontinuity Design (RDD)

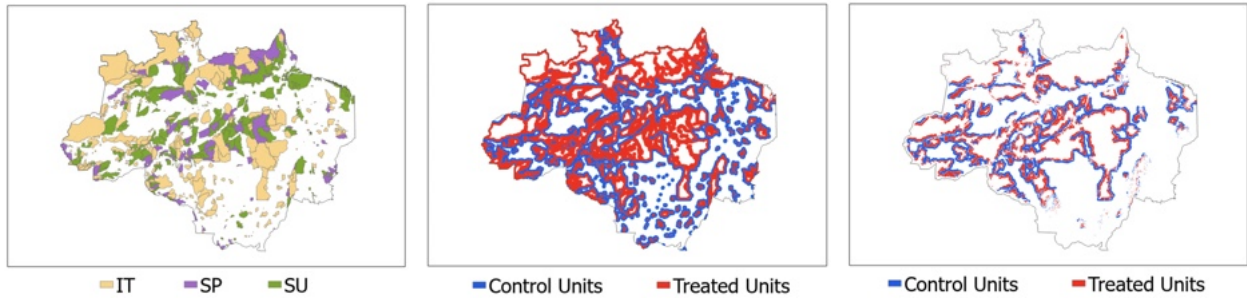


Figure S2: Protected areas

Figure S3: Grids within 20km

Figure S4: Sample of Grids

Figure S5: RDD Design and Sample Construction

Notes: Panel (a) shows the spatial regression discontinuity design used to estimate the effect of protected areas on deforestation. Panels (b)–(d) illustrate how sample grids are constructed within 12km of protected area boundaries and selected for the estimation.

Where c is the cut-off and T_i is a binary variable equal to one if $X \geq c$ and $c - h \leq X \leq c + h$, where h is the optimal bandwidth that minimizes mean square error. The term $f(X_i - c)$ is a polynomial representing the functional form used to fit the data. In our analysis, we employ a local linear regression (e.g., a first-order polynomial) with a triangular kernel, following (72), and select the bandwidth (h) to minimize Mean Square Error using the (73) algorithm implemented in the “rdrobust” package in R.

To assess the robustness of our estimates, we conduct a series of sensitivity analyses, presented in Appendix 3. First, we test alternative bandwidth choices ranging from 6km to 20km around the boundaries of protected areas. The estimated treatment effects remain highly stable across this range (see Figures S11, S12, and S13 for IT, SP, and SU, respectively), confirming that our results are not driven by bandwidth selection. Second, we re-estimate our regression discontinuity at artificial cut-off points located ± 2 and ± 5 km from the actual PA boundaries. Because no policy discontinuity exists at these placebo boundaries, any significant effects would indicate potential bias from spatial trends rather than the treatment itself. Table S17 shows that estimates at placebo cut-offs are near zero, indicating no such bias. Finally, a crucial assumption of this design is that potential outcomes remain continuous at the threshold. While this assumption cannot be directly tested, we assess its observable implications in Appendix Tables S14, S15, and S16, showing that pre-treatment covariates are continuous at the threshold. Together, these robustness checks provide strong evidence that our findings are not sensitive to specific modeling choices.

Difference-in-Discontinuities Design

We also implement a difference-in-discontinuities (diff-in-disc) design (44), which combines elements of difference-in-differences and geographic regression discontinuity. This approach allows us to compare deforestation rates just inside and outside the borders of protected areas, areas that differ only in protection status, before and after the 2012 governance shift (and after Bolsonaro took office in 2018). By leveraging both spatial and temporal variation, we isolate the causal effect of these policy changes while controlling for time-invariant characteristics that could influence deforestation patterns.

We estimate the diff-in-disc design using the following specification:

$$Def_{it} = \alpha + \beta_1 RDD_i + \beta_2 Post_t + \beta_3 (RDD_i \times Post_t) + \gamma_i + \delta_t + \epsilon_{it} \quad (S2)$$

Where Def_{it} denotes deforestation in grid cell i in year t ; RDD_i is a spatial treatment variable equal to 1 for grid cells inside a PA, and 0 for those just outside the PA boundary (based on the same specification as in Equation S1). $Post_t$ is a temporal indicator equal to 1 for years after 2012 (or 2018), capturing the weakening of environmental institutions. The interaction term $RDD_i \times Post_t$ identifies the diff-in-disc treatment effect - our main coefficient of interest. Finally, γ_i and δ_t denote year and PA fixed effects, respectively, and ϵ_{it} is the error term. Standard errors are clustered at the PA level.

The validity of this approach rests on two primary assumptions (44). First, as in standard RDD designs, potential outcomes must be smooth around the geographic boundary; we demonstrate this in the Tables S14, S15, and S16. Second, PA with similar characteristics but differing only in their protection status should exhibit parallel trends in deforestation before the weakening of institutions in 2012. Overall, as shown in Figure S18, this assumption largely holds, with only SP showing a minor pre-treatment deviation.

Supplementary Text

Protected Areas in Brazil

Brazil's conservation system includes conservation units, mosaics, and ecological corridors - different types of territorial planning aimed at the protection of biodiversity. In this paper, we look at three different types of designated public forest areas: (i) indigenous territories (ITs), (ii) sustainable use areas (SUs), and (iii) strictly protected areas (PAs). ITs cover about 24% of the land area in the Legal Amazon, while SUs and PAs cover about 18% of this area. While they are all designated public forests, they are governed by different rules and agencies and differ in their CPR management systems, especially with regards to the degree of rights and responsibilities entrusted to local communities within them.

Indigenous Territories (ITs)

Indigenous territories are administered by FUNAI (Fundação Nacional do Índio⁸), the national indigenous agency that exists under the Ministry of Justice and Public Security. ITs in Brazil gain their full property rights through a legal process called demarcation. Demarcation consists of a four-step process involving (1) an anthropological study to identify the physical boundaries of the territory, (2) the approval of FUNAI, (3) the approval of the Minister of Justice and (4) the homologation by Presidential decree and registration in the national land registry. This process further holds that, prior to the presidential homologation, any third party can contest the demarcation of a territory and non-indigenous parties living on said territory will be resettled and financially compensated. Once homologated, indigenous territories gain their full property rights as enumerated in the 1988 Brazilian Constitution.

The Constitution states that Indigenous peoples' socio-political rights and original right to land is incumbent upon the Union's demarcation of these territories (Article 231) and recognizes these homologated territories as "those indispensable for the preservation of environmental resources necessary for their well-being" (74). Article 231 poses that Indigenous peoples have "the exclusive usufruct of the riches of the soil, rivers and lakes existing thereon" (74) while exploitation rights of the subsoil remain vested in the State. Additionally, the Union has the constitutional "responsi-

⁸National Foundation for the Indigenous peoples

bility to delineate these lands and to protect and ensure respect for all their property” (74). Once homologated, a territory becomes the permanent possession of its Indigenous peoples, contestation is limited and extractive activities carried out by external actors can only occur after consulting the communities and the National Congress.

Strictly Protected Areas (SPs) and Sustainable Use Areas (SUs)

The National System of Conservation Units (SNUC) was created in July 2000 by Law 9985/2000 as the main agency, under the Ministry of the Environment, in charge of creating and managing Brazil’s conservation unit system. The National Council for the Environment (CONAMA) is the consultative body in charge of monitoring the implementation of the SNUC.

The SNUC includes federal, state and municipal conservation units which can either be public or private lands. At the federal level, the Chico Mendes Institute for Biodiversity (ICMBio) is tasked with the administration, management and monitoring of these protected areas while IBAMA is tasked with licensing, monitoring and enforcement (75). ICMBio formalized its monitoring program in 2007 and consists in trainings, data collection and providing subsidies for conservation planning and assessments. State and municipal governments have their own agencies in charge of PA management supported by ICMBio, non-governmental organizations (NGOs) and international development agencies and projects (75). NGOs provide an important complementary role to these governmental agencies with supporting local communities, managing conservation units and monitoring their effectiveness (75).

There are 12 types of PAs in Brazil which fit into two larger categories: strictly protected areas (SPs) and sustainable use areas (SUs). Sustainable use areas include environmental protection areas, areas of relevant ecological interest, national forests, extractive reserves, fauna reserves, sustainable development reserves, and private natural heritage reserves. The creation of these various types of SUs emerged from local social movements. As such, the motivation behind them was initially not driven by an objective of conservation but rather as a way to secure tenure rights for local communities and avoid encroachment by outside interests. Biological conservation is the secondary goal of these areas as they allow for various forms of land use and human presence (76). The objective of SUs is to make conservation and sustainable use of natural resources compatible.

Strictly protected areas include ecological stations, biological reserves, national parks, national

monuments and wildlife refuges. The primary goal of these areas is biodiversity conservation (76) where only the indirect use of natural resources is allowed. Activities such as the consumption, collection or destruction of resources are illegal while activities related to recreation, ecological tourism, research and education may be carried out (77).

The main differences between SUs and SPs are related to (i) land use and (ii) human occupation. SPs only allow for the indirect use of natural resources and at most allow for human visitation. SU areas allow for the sustainable use of natural resources and for human occupation whether these are private actors or local communities (not Indigenous).

Forest Legislation in Brazil

The Brazilian Forest Code was enacted in 1965. After very high clearing in the 1980s–early 2000s, Brazil assembled a policy bundle to curb deforestation. By the late 1990s the Forest Code had become the backbone of environmental law (78). A 2001 update maintained strict protection standards, including the requirement that private landowners in the Legal Amazon set aside 80% of their property as Legal Reserve. After deforestation peaked in 2004, annual rates fell sharply in the subsequent years.

A large share of this decline is attributed to two complementary policy fronts (79). First, the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPC-DAm, 2004) coordinated federal, state, and municipal actions and institutionalized near real-time monitoring (DETER) to target enforcement; the 2004–2009 period also expanded conservation units and professionalized management and policing. Second, beginning in 2007–2008, Brazil layered command-and-control and credit instruments: Presidential Decrees 6,321/2007 (priority-municipalities “blacklist”) and 6,514/2008 (sanctions and administrative procedures), alongside National Monetary Council Resolution 3,545/2008 (conditioning rural credit on environmental compliance). Together these measures targeted high-deforestation municipalities, tightened sanctioning, and restricted subsidized finance for non-compliant producers (79).

Forest Code of 2012 The Forest Code was amended in 2012. Substantively, the reform retained Legal Reserve and Permanent Preservation Area rules, created the Rural Environmental Registry (CAR/SICAR) and Environmental Regularization Programs (PRA), and added provisions on fire management, forest carbon, and payments for ecosystem services. At the same time, it granted amnesties and relief for pre-22 July 2008 clearing via three channels: (i) a blanket waiver of Legal Reserve recomposition for properties up to four fiscal modules (Art. 67); (ii) recognition of ‘consolidated’ APP uses with reduced restoration widths that increase with property size (Art. 61-A); and (iii) suspension/conversion of pre-2008 administrative fines upon enrollment and compliance with state PRAs (Art. 59, §§4–5). This resulted in reducing restoration liabilities nationwide (from roughly 50 million to 21 million hectares in one widely cited estimate) (78). In 2018, Brazil’s Supreme Court upheld the constitutionality of most of these provisions, including the amnesty for pre-2008 illegal clearing, reinforcing the reform’s lenient treatment of legacy liabilities. (80).

The 2012 outcome reflected sustained political pressure from the agricultural caucus (bancada ruralista) and allied interests in Congress. Analyses of the legislative process document a broad, multi-partisan rural bloc that successfully reframed and watered down several restoration and compliance requirements during committee bargaining and floor amendments; voting patterns and financing links further indicate agribusiness influence over the final text (81 82 83). While the revised Code introduced useful implementation tools (CAR/PRA), the combination of amnesties and relaxed obligations, together with subsequent regulatory choices, left the post-2012 regime weaker on net than the pre-reform framework (78).

Since 2012, there has been a steady shift toward legal and administrative changes that, on net, weakened environmental safeguards and institutional capacity. Many proposals sought to alter the recognition and governance of Indigenous territories (e.g., shifting demarcation authority toward Congress and changing recognition criteria), relax environmental licensing, and expand pathways to regularize occupations of public lands. Even when Congress did not enact these proposals, executive decrees, non-legislative acts, budget contingencies, and personnel changes reduced enforcement capability and willingness to act inside environmental agencies. Illustrative attempts include: (i) reshaping Indigenous-territory recognition and governance (PEC 215/2000; Portaria 68/2017; PL 490/2007; PL 191/2020); (ii) limiting public-sector capacity via the federal spending cap (PEC 241/2016 → EC 95/2016); (iii) streamlining regularization of illegally claimed lands in ways that risked rewarding occupation and clearing (MPV 867/2018; Law 13.465/2017; MP 910/2019; PL 2633/2020); and (iv) relaxing environmental licensing requirements (PL 3729/2004, renum. PL 2159/2021). These measures—and earlier pro-environmental pillars from 2004–2008—are detailed in Table S1 and Table S3.

Bolsonaro years (2019–2022) From 2019 onward, a new wave of executive and legislative initiatives further shifted the institutional balance away from deterrence and oversight (Table S3). Administratively, Decree 9,741/2019 introduced budget contingencies that constrained discretionary execution across ministries, while Decree 9,806/2019 reconstituted the National Environmental Council (CONAMA), reducing civil-society representation and centralizing agenda control within the federal Executive. In parallel, Decree 9,760/2019 altered the sanctioning workflow by inserting a mandatory pre-enforcement conciliation phase, changing timelines and the sequencing of

Legislation	Description	Status/Year	Direction
PPCDAm (Inter-ministerial Plan)	Action Plan to prevent/control deforestation in the Legal Amazon (launched; multi-phase)	2004	strengthen
Law 11.284/2006 (Public Forest Management)	Creates SFB and FNDF; enables sustainable forest concessions	2006	strengthen
Law 11.516/2007 (Creates ICMBio)	Establishes ICMBio to manage, police and monitor federal conservation units	2007	strengthen
Decree 6.321/2007	Priority-municipalities “blacklist”; integrated enforcement/embargo actions	2007	strengthen
Res. CMN 3.545/2008	Conditions rural credit in the Amazon on environmental compliance	2008	strengthen
Decree 6.514/2008	Updates environmental infractions, sanctions and administrative procedures	2008	strengthen
Law 11.952/2009 (Terra Legal)	Federal land regularization in Amazon Legal (facilitates titling of occupations)	2009	mixed

Table S1: Major federal legal/administrative acts affecting forest/land-use governance in the Brazilian Amazon, before 2012.

administrative penalties.

On the regulatory front, the government advanced a broad overhaul of environmental licensing. The long-running licensing bill (PL 3729/2004, renumbered PL 2159/2021) moved forward in the Chamber with provisions that streamlined procedures and narrowed the scope of projects subject to full studies and consultations. In 2020, a reconfigured CONAMA approved Resolution 500/2020 that revoked protections for restingas and mangroves—subsequently suspended by court order—illustrating the use of infra-legal acts to revise long-standing safeguards.

Territorial governance was also targeted. FUNAI’s Normative Instruction No. 9/2020 changed how land certification interacts with Indigenous territories that are not yet fully homologated, with implications for claims and cadastral regularity in contested frontiers. In Congress, PL 490/2007 (the “Marco Temporal” framework) gained momentum in committees, while PL 191/2020 proposed authorizing mining, hydrocarbons, and hydropower in Indigenous lands and obtained urgency status

Legislation	Description	Status/Year	Direction
Law 12.651/2012 (New Forest Code)	New Code with amnesties/reliefs + CAR/PRA architecture	2012	weaken
Decree 7.830/2012	Implements SICAR/CAR and general PRA rules (operationalization)	2012	mixed
EC 95/2016 (ex-PEC 241)	Constitutional spending cap constraining environmental budgets	2016	weaken
MPV 756/2016	Redraws PA limits (e.g., Jamanxim); Congress text vetoed	Vetoed 2017	weaken (proposed)
Portaria MJ 68/2017	Alters TI demarcation procedure; revoked days later (replaced by Port. 80)	Issued/revoked 2017	weaken (attempt)
Law 13.465/2017	Broad land-regularization changes (streamlines titling/regularization)	2017	weaken
PEC 65/2012	Would relax environmental licensing requirements (EIA)	Archived 2018	weaken (proposed)
PEC 215/2000	Shifts Indigenous land demarcation power to Congress	Pending (2018)	weaken (proposed)
MPV 867/2018	Extends PRA/Forest Code deadlines; approved in Chamber, lapsed in Senate	Lapsed 2019	weaken (proposed)

Table S2: Major federal legal/administrative acts affecting forest/land-use governance in the Brazilian Amazon, 2012–2018.

in 2022, accelerating its processing.

Land-regularization pathways were expanded and simplified. MP 910/2019 proposed self-declaratory titling rules for federal lands and, after lapsing, its core was reintroduced via PL 2633/2020, which was approved in the Chamber in 2021 and proceeded to the Senate. Finally, Portaria Casa Civil No. 667/2022 formalized a priority legislative agenda that bundled several of these initiatives under “urgent” status, structuring congressional time and voting to advance the deregulatory package.

Legislation	Description	Status/Year	Direction
Decree 9.741/2019	2019 budget contingency (reduces exec. capacity incl. env. agencies)	2019	weaken
Decree 9.760/2019	Alters fines/conciliation procedure for environmental infractions	2019	weaken
Decree 9.806/2019	Reconstitutes CONAMA, reducing civil-society representation and shifting agenda control	2019	weaken
MP 910/2019	Self-declaration land regularization; replaced by PL 2633/2020	Lapsed 2020	weaken (proposed)
CONAMA Res. 500/2020	Revokes protections for restingas/mangroves; subsequently suspended by STF (precautionary)	2020; suspended	weaken (attempt)
PL 3729/2004 (renum. PL 2159/2021)	New environmental licensing framework	Approved Chamber 2021; pending Senate 2022	weaken
PL 490/2007	“Marco Temporal” framework for IT demarcations	CCJ approved 2021; plenary pending 2022	weaken
FUNAI Normative Instruction 9/2020	Alters land certification rules intersecting non-homologated Indigenous territories	2020	weaken
PL 2633/2020	Land regularization (post-MP 910; autodeclaration/relaxed checks)	Approved Chamber 2021; in Senate 2022	weaken
PL 191/2020	Authorizes mining/energy in Indigenous lands; urgency approved Mar/2022	approved; awaiting commission (2022)	weaken
Portaria Casa Civil 667/2022	Sets “priority/urgent” executive agenda (includes several items above)	2022	weaken (meta-agenda)

Table S3: Major federal legal/administrative acts affecting forest/land-use governance in the Brazilian Amazon, 2019–2022.

Federal environmental budgets

This appendix presents trends in the federal budget allocated to the Ministry of the Environment in Brazil between 2000 and 2022. Figure [S6](#) shows the proposed budget as a share of total federal spending, while Figure [S7](#) displays the executed (actual) budget share. Both series illustrate the increase in allocations during the PPCDAM period, peaking around 2010, followed by sustained declines after the 2012 Forest Code reform, with sharper reductions following the election of Jair Bolsonaro in 2018. These trends provide quantitative evidence of the erosion of fiscal capacity for environmental governance over our study period. Federal budget data is obtained from the Brazilian Government's planning and budget system website (*Sistema Integrado de Planejamento e Orçamento*, SIOP).

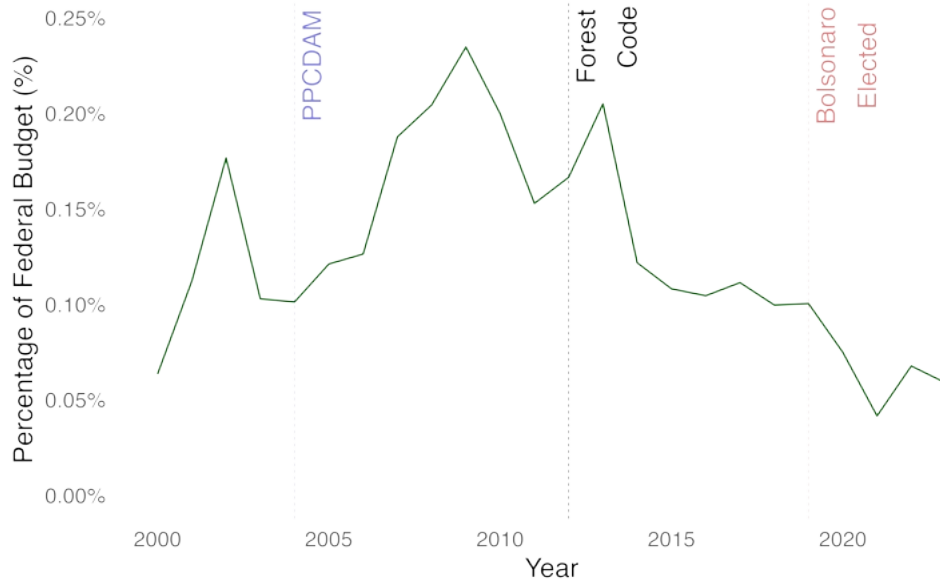


Figure S6: Proposed Budget

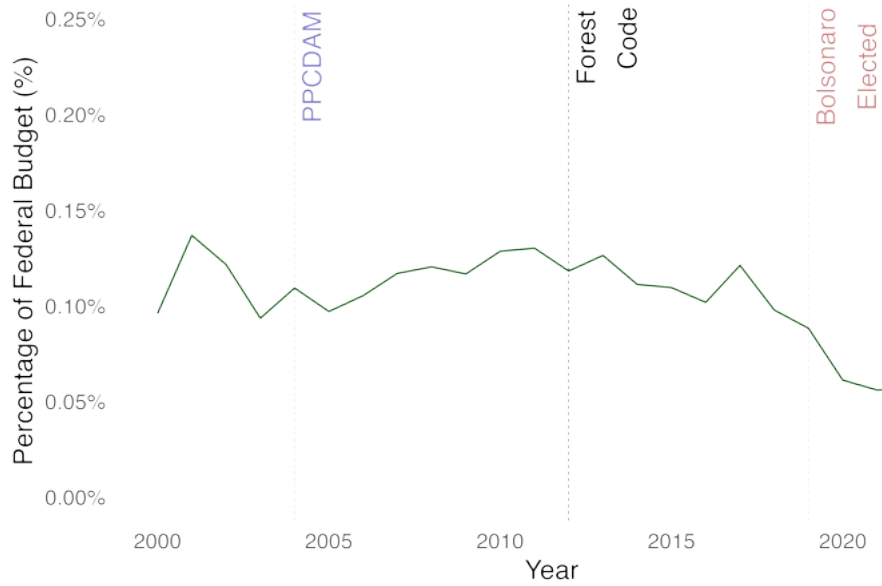


Figure S7: Executed Budget

Descriptive Statistics

This subsection reports descriptive statistics for the key variables used in our analysis, disaggregated by land designation category. The tables provide summary measures (mean, standard deviation, minimum, and maximum) for deforestation and geographic covariates such as distances to different types of protected areas, roads, rivers, and cities, as well as elevation, slope, and hillshade. Table [S4](#) presents descriptive statistics for the sample inside and around ITs, table [S5](#) does so for SPs, table [S6](#) presents descriptives for SUs.

Table S4: Indigenous Territories

Statistic	N	Mean	St. Dev.	Min	Max
Deforestation (km2)	57,292	0.02	0.11	0.00	3.47
Deforestation (%)	57,292	0.52	2.68	0.00	86.64
IT Dummy	54,524	0.17	0.38	0	1
Distance to IT (km)	57,292	-2.79	6.37	-12.00	12.00
Distance to Roads (2005, km)	57,292	81.74	75.58	0.00	403.87
Distance to Rivers (km)	57,292	75.97	55.37	0.00	262.72
Distance to Cities (km)	57,292	572.40	255.40	76.14	1,410.05
Elevation (m)	57,292	166.38	84.45	33.56	618.61
Hillshade	57,292	180.25	1.45	166.96	190.87
Slope	57,292	0.58	0.70	0.00	7.78

Table S5: Strictly Protected

Statistic	N	Mean	St. Dev.	Min	Max
Deforestation (km2)	89,812	0.01	0.08	0.00	2.96
Deforestation (%)	89,812	0.32	2.03	0.00	73.90
SP Dummy	89,812	0.10	0.30	0	1
Distance to SP (km)	89,812	-0.56	6.42	-12.00	12.00
Distance to Roads (2005, km)	89,812	61.61	50.66	0.00	388.30
Distance to Rivers (km)	89,812	101.27	59.67	0.00	242.73
Distance to Cities (km)	89,812	467.61	124.98	156.66	1,396.23
Elevation (m)	89,812	134.84	78.52	36.52	647.75
Hillshade	89,812	180.32	1.36	168.58	194.80
Slope	89,812	0.60	0.57	0.00	6.53

Table S6: Sustainable Use

Statistic	N	Mean	St. Dev.	Min	Max
Deforestation (km2)	124,251	0.02	0.10	0.00	3.87
Deforestation (SU Dummy)	124,251	0.10	0.30	0	1
Distance to SU (km)	124,251	-1.20	6.24	-12.00	12.00
Distance to Roads (2005, km)	124,251	70.93	82.67	0.00	403.87
Distance to Rivers (km)	124,251	93.94	66.72	0.00	263.19
Distance to Cities (km)	124,251	529.97	225.52	71.36	1,400.49
Elevation (m)	124,251	145.67	75.55	5.77	669.69
Hillshade	124,251	180.28	1.50	154.72	197.93
Slope	124,251	0.62	0.66	0.00	10.00

Distribution of Treatment Timing

This subsection provides plots illustrating the evolution of our treatment over time. Figure S8 shows how ITs, SP, and SUs were progressively recognized from the 1940s until now.

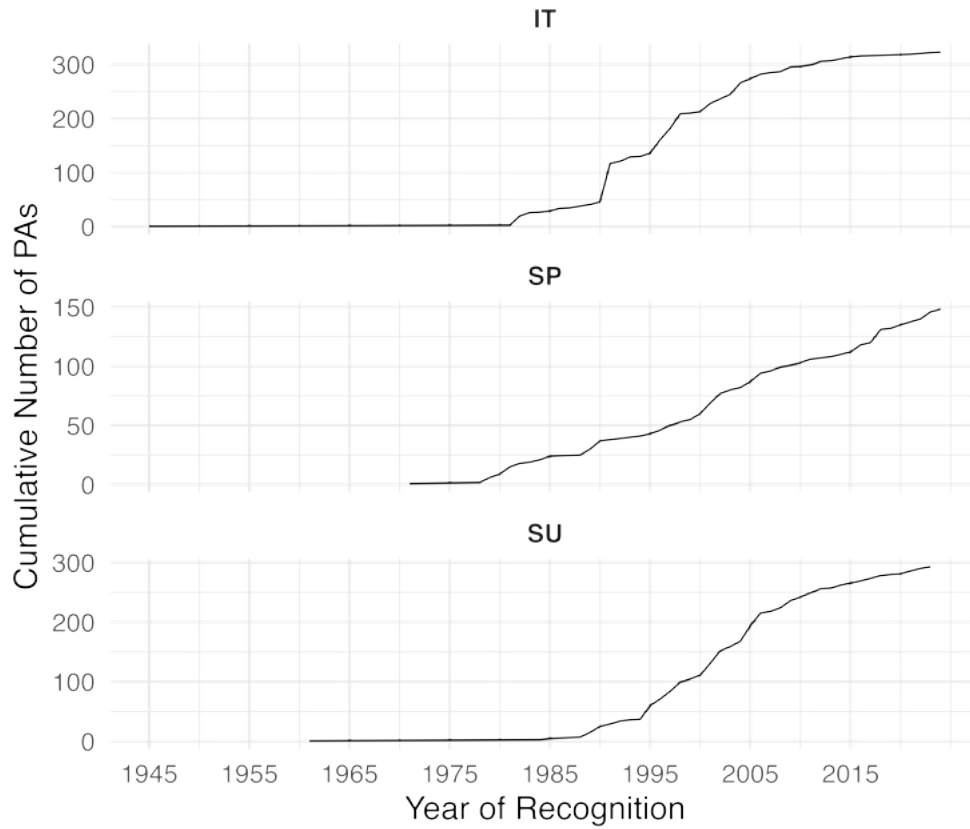


Figure S8: Cumulative Number of PAs Designated by Type

Yearly Geographic Regression Discontinuity Analyses

This section reports yearly geographic regression discontinuity estimates for Indigenous Territories (ITs), Strictly Protected Areas (SPs), and Sustainable Use Areas (SUs) over the 2004–2022 period (see Figure S9). The yearly estimates allow us to trace the temporal dynamics of the discontinuity in deforestation rates between protected and non-protected lands, capturing changes associated with major institutional and political shifts. We present results for the full sample (Table S8) and separately for the arc of deforestation and non-arc regions (Tables S9, S10, and S11, respectively), using a 12km buffer bandwidth around PA boundaries. These coefficients report the estimates shown in Figure 3 in the main text.

For ITs, coefficients are consistently negative and statistically significant across most years, indicating a persistent protective effect. The magnitude of the discontinuity fluctuates over time, with a gradual weakening in the years immediately preceding the 2012 Forest Code reform, followed by a partial recovery (Table S8). The post-2018 period, coinciding with the Bolsonaro administration, is characterized by some of the largest absolute discontinuities, particularly in non-arc regions (Table S9).

SPs exhibit similar temporal patterns but with larger magnitudes in certain years, especially post-2018, when the difference in deforestation between protected and adjacent lands widened substantially in both arc and non-arc areas (Tables S8 and S10). SUs display smaller and more variable effects in earlier years, but show pronounced increases in the discontinuity in the later period, especially after 2018, consistent with an intensification of surrounding deforestation pressures (Tables S8 and S11).

Table S7: RDD Estimates by PA

Panel A: Indigenous Territories							
	Year	Full Sample (12k)		Arc (12k)		Non-Arc (12k)	
		Estimate	S.E.	Estimate	S.E.	Estimate	S.E.
	PPCDAM I - 2004-2007	-0.812***	0.170	-1.437***	0.245	-0.215**	0.103
	PPCDAM II - 2008-2011	-0.397***	0.099	-0.677***	0.162	-0.126*	0.069
	Forest Code (2012-2018)	-0.358***	0.079	-0.569***	0.126	-0.158**	0.064
	Bolsonaro Administration (2019-2022)	-0.493***	0.147	-0.729***	0.248	-0.271**	0.105
Panel B: Strictly Protected Areas							
	Year	Full Sample (12k)		Arc (12k)		Non-Arc (12k)	
		Estimate	S.E.	Estimate	S.E.	Estimate	S.E.
	PPCDAM I - 2004-2007	-0.262	0.162	-0.598***	0.120	0.058	0.230
	PPCDAM II - 2008-2011	-0.225**	0.076	-0.444***	0.111	-0.056	0.095
	Forest Code (2012-2018)	-0.353***	0.099	-0.557***	0.132	-0.179	0.123
	Bolsonaro Administration (2019-2022)	-0.882***	0.265	-0.941***	0.255	-0.848**	0.397
Panel C: Sustainable Use Areas							
	Year	Full Sample (12k)		Arc (12k)		Non-Arc (12k)	
		Estimate	S.E.	Estimate	S.E.	Estimate	S.E.
	PPCDAM I - 2004-2007	-0.183*	0.107	-0.276**	0.139	-0.043**	0.022
	PPCDAM II - 2008-2011	-0.152**	0.072	-0.257**	0.105	-0.024	0.020
	Forest Code (2012-2018)	-0.288**	0.097	-0.356**	0.125	-0.222*	0.124
	Bolsonaro Administration (2019-2022)	-0.901***	0.243	-0.937**	0.302	-0.868**	0.348

Notes: This table reports RDD estimates from Equation S1 and Figure 3, where the dependent variable is the percentage change in deforestation. Significance: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

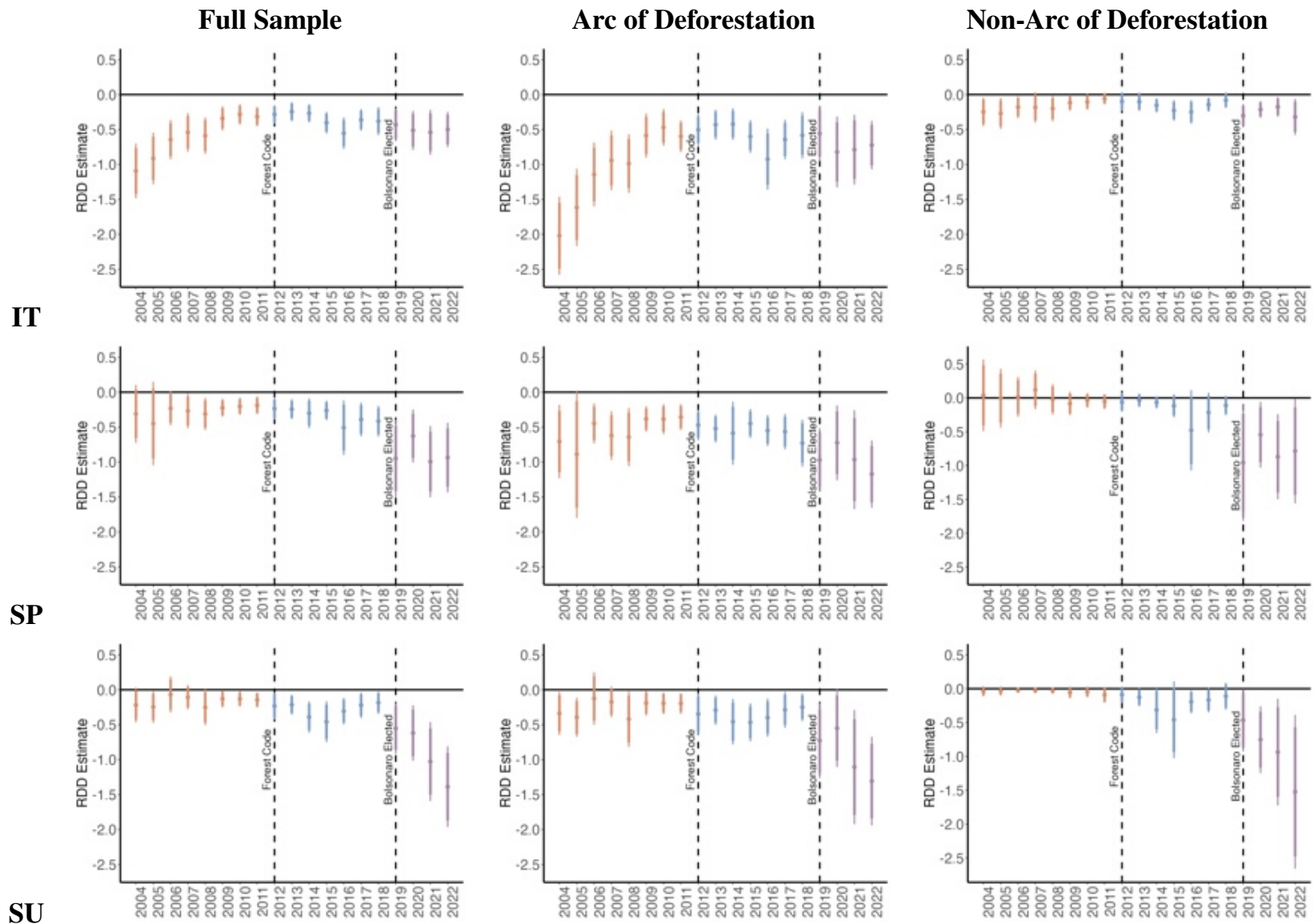


Figure S9: RDD estimates for IT, SP, and SU (rows), showing yearly coefficients for the Full Sample, Arc, and Non-Arc of Deforestation (columns) using a 12km bandwidth. Vertical dashed lines mark the 2012 Forest Code reform and the 2018 Bolsonaro election.

Table S8: RDD Estimates - IT, SP, and SU

Year	IT (12k)		SP (12k)		SU (12k)	
	Estimate	S.E.	Estimate	S.E.	Estimate	S.E.
2004	-1.094***	0.200	-0.310	0.212	-0.218*	0.127
2005	-0.914***	0.189	-0.449	0.305	-0.246**	0.115
2006	-0.644***	0.143	-0.230*	0.125	-0.067	0.132
2007	-0.540***	0.141	-0.268**	0.126	-0.107	0.089
2008	-0.588***	0.133	-0.312***	0.117	-0.250*	0.131
2009	-0.341***	0.088	-0.224***	0.065	-0.129**	0.063
2010	-0.283***	0.075	-0.202***	0.063	-0.130**	0.057
2011	-0.315***	0.071	-0.188***	0.065	-0.144***	0.056
<i>Forest Code Reform</i>						
2012	-0.284***	0.068	-0.236***	0.080	-0.232**	0.099
2013	-0.244***	0.070	-0.244***	0.072	-0.213***	0.073
2014	-0.267***	0.067	-0.301***	0.108	-0.390***	0.115
2015	-0.403***	0.078	-0.261***	0.070	-0.457***	0.149
2016	-0.552***	0.115	-0.507**	0.199	-0.306***	0.097
2017	-0.362***	0.079	-0.389***	0.123	-0.220**	0.094
2018	-0.379***	0.103	-0.415***	0.112	-0.184**	0.082
<i>Bolsonaro Administration</i>						
2019	-0.430***	0.122	-0.948***	0.285	-0.552***	0.187
2020	-0.511***	0.142	-0.626***	0.194	-0.619***	0.203
2021	-0.540***	0.165	-0.994***	0.260	-1.026***	0.288
2022	-0.500***	0.129	-0.935***	0.254	-1.387***	0.295

Notes: This table reports RDD estimates from Equation S1, where the dependent variable is the percentage change in deforestation. Significance: * p<0.1; ** p<0.05; *** p<0.01.

Table S9: RDD Estimates - Arc of Deforestation - Indigenous Territories

	Arc (12k)		Non-Arc (12k)	
Year	Estimate	S.E.	Estimate	S.E.
2004	-2.021***	0.286	-0.246**	0.106
2005	-1.615***	0.283	-0.269**	0.113
2006	-1.143***	0.233	-0.180**	0.080
2007	-0.942***	0.218	-0.184*	0.111
2008	-0.987***	0.214	-0.200**	0.093
2009	-0.586***	0.161	-0.117**	0.058
2010	-0.469***	0.133	-0.104*	0.057
2011	-0.596***	0.116	-0.059	0.042
<i>Forest Code Reform</i>				
2012	-0.504***	0.116	-0.098	0.068
2013	-0.430***	0.109	-0.102	0.067
2014	-0.422***	0.115	-0.154***	0.052
2015	-0.599***	0.120	-0.228***	0.075
2016	-0.923***	0.223	-0.248***	0.087
2017	-0.643***	0.145	-0.142***	0.052
2018	-0.582***	0.169	-0.080	0.057
<i>Bolsonaro Administration</i>				
2019	-0.557***	0.203	-0.301***	0.085
2020	-0.820***	0.258	-0.212***	0.061
2021	-0.788***	0.255	-0.175**	0.072
2022	-0.723***	0.176	-0.319**	0.132

Notes: This table reports RDD estimates from Equation [S1](#) where the dependent variable is the percentage change in deforestation. **Significance Levels:** * p<0.1; ** p<0.05; *** p<0.01.

Table S10: RDD Estimates - Arc of Deforestation - Strictly Protected Areas

	Arc (12k)		Non-Arc (12k)	
Year	Estimate	S.E.	Estimate	S.E.
2004	-0.706***	0.268	0.039	0.271
2005	-0.889*	0.465	-0.004	0.222
2006	-0.448***	0.146	0.015	0.151
2007	-0.622***	0.178	0.118	0.146
2008	-0.642***	0.212	-0.023	0.115
2009	-0.383***	0.092	-0.084	0.089
2010	-0.385***	0.109	-0.037	0.055
2011	-0.356***	0.095	-0.054	0.057
<i>Forest Code Reform</i>				
2012	-0.471***	0.112	-0.063	0.072
2013	-0.521***	0.102	-0.037	0.051
2014	-0.588**	0.230	-0.066	0.045
2015	-0.448***	0.105	-0.116	0.087
2016	-0.550***	0.113	-0.479	0.303
2017	-0.565***	0.129	-0.216	0.150
2018	-0.729***	0.171	-0.112	0.074
<i>Bolsonaro Administration</i>				
2019	-0.969***	0.232	-0.956**	0.439
2020	-0.724***	0.273	-0.545**	0.248
2021	-0.965***	0.361	-0.869***	0.321
2022	-1.172***	0.245	-0.786**	0.393

Notes: This table reports RDD estimates from Equation [S1](#) where the dependent variable is the percentage change in deforestation. **Significance Levels:** * p<0.1; ** p<0.05; *** p<0.01.

Table S11: RDD Estimates - Arc of Deforestation - Sustainable Use Areas

	Arc (12k)		Non-Arc (12k)	
Year	Estimate	S.E.	Estimate	S.E.
2004	-0.338**	0.158	-0.038	0.038
2005	-0.394***	0.143	-0.032	0.034
2006	-0.124	0.193	-0.024	0.019
2007	-0.173	0.112	-0.025	0.022
2008	-0.419**	0.203	-0.027	0.024
2009	-0.190**	0.092	-0.054	0.044
2010	-0.193**	0.080	-0.046	0.041
2011	-0.194**	0.076	-0.090	0.061
<i>Forest Code Reform</i>				
2012	-0.346**	0.154	-0.089	0.063
2013	-0.291**	0.107	-0.126*	0.068
2014	-0.456***	0.167	-0.314*	0.173
2015	-0.466***	0.139	-0.458	0.290
2016	-0.398***	0.140	-0.193**	0.088
2017	-0.286**	0.132	-0.166*	0.094
2018	-0.250**	0.101	-0.111	0.103
<i>Bolsonaro Administration</i>				
2019	-0.726***	0.275	-0.465**	0.236
2020	-0.550*	0.284	-0.753***	0.252
2021	-1.106***	0.417	-0.937**	0.403
2022	-1.307***	0.323	-1.523***	0.580

Notes: This table reports RDD estimates from Equation [S1](#) where the dependent variable is the percentage change in deforestation. **Significance Levels:** * p<0.1; ** p<0.05; *** p<0.01.

Difference-in-Discontinuities Analyses

This appendix reports the full regression tables for our difference-in-discontinuities (Diff-in-Disc) estimates of the effects of Protected Areas on deforestation, using two institutional breakpoints: the 2012 Forest Code reform and the election of Jair Bolsonaro in 2018. For each event, we estimate separate models for Indigenous Territories (ITs), Strictly Protected Areas (SPs), and Sustainable Use Areas (SUs), disaggregated by the arc of deforestation and non-arc regions. The “Inside” coefficient captures the baseline discontinuity at PA boundaries in the pre-break period, while the “Inside \times Post” coefficient measures the change in that discontinuity after the institutional shift.

Across both breakpoints, results show that protected areas generally became more effective relative to surrounding lands when national enforcement capacity declined. Heterogeneity analysis by arc and non-arc areas reveals that post-shift gains in relative effectiveness were often more pronounced in zones outside the historical arc of deforestation, consistent with the expansion of pressures into previously remote areas. These findings correspond closely to the graphical estimates presented in Section [2.2](#).

1. 2012 Forest Code Reform (Table [S12](#))

For ITs, pre-reform discontinuities are strongly negative across all subsamples, indicating lower deforestation inside ITs relative to surrounding lands before 2012. Post-2012, the “Inside \times Post” coefficient is negative but small and only significant outside the arc, suggesting modest additional gains in these less historically pressured regions. For SPs, we find significant post-reform strengthening in all subsamples, with some of the largest gains outside the arc (-0.3790^{**}), consistent with expanded deterrence effects in frontier areas. For SUs, the post-reform effect is negative and significant in all subsamples, with the largest magnitude outside the arc (-0.5218^{**}), implying that these multiple-use areas also improved in relative effectiveness following the reform.

2. 2018 Bolsonaro Election (Table [S13](#))

Under Bolsonaro, the post-2018 effects are uniformly negative, indicating a stronger relative performance of PAs even amidst steep declines in national-level enforcement. For ITs, gains are statistically significant for the full sample and non-arc areas. SPs register substantial and significant post-2018 effects in all subsamples, with the largest outside the arc (-0.6652^{**}).

SUs experience the largest observed post-shift effects of any breakpoint, especially in the arc (-0.7343^{***}) and outside (-0.88561^{**}), consistent with strong localized resistance to rising deforestation pressures.

Taken together, these results show that, across two major governance shocks, all PA categories exhibit resilience and, in many cases, strengthened relative effectiveness. The particularly large and significant effects outside the arc highlight the role of PAs in buffering emerging frontiers of deforestation. These patterns align closely with the visual evidence presented in Figure 4 and reinforce our interpretation of PAs as institutions that adapt and persist even under adverse political conditions.

Table S12: Difference-in-Discontinuities: Effects of PAs on Deforestation Before and After 2012

Panel A: Indigenous Territories			
	Full Sample	Arc of Def.	Non-Arc of Def.
	(1)	(2)	(3)
Inside	-0.3305*** (0.0667)	-0.6034*** (0.1170)	-0.1120*** (0.0364)
Inside X Post-2011	-0.0795 (0.0536)	-0.0524 (0.0908)	-0.0950** (0.0398)
Observations	278,315	198,794	136,642
R ²	0.06441	0.06725	0.04782
Within R ²	0.01215	0.02034	0.00590
Panel B: Strictly Protected Areas			
	Full Sample	Arc of Def.	Non-Arc of Def.
	(1)	(2)	(3)
Inside	-0.2368*** (0.0621)	-0.4083*** (0.0983)	-0.0706 (0.0452)
Inside X Post-2011	-0.2994** (0.1135)	-0.2184** (0.0830)	-0.3790** (0.1744)
Observations	118,818	61,226	52,512
R ²	0.03661	0.04391	0.03200
Within R ²	0.01281	0.01913	0.00855
Panel C: Sustainable Use Areas			
	Full Sample	Arc of Def.	Non-Arc of Def.
	(1)	(2)	(3)
Inside	-0.1821*** (0.0427)	-0.2607*** (0.0594)	-0.0649* (0.0375)
Inside X Post-2011	-0.4199*** (0.1123)	-0.3385*** (0.0964)	-0.5218** (0.2134)
Observations	244,353	138,173	77,600
R ²	0.04217	0.04663	0.03237
Within R ²	0.00957	0.00955	0.00917

Notes: This table presents results from difference-in-discontinuities regressions from equation [S2](#) where the dependent variable is the percentage change in deforestation. Panel A shows results for Indigenous Territories, Panel B for Strictly Protected Areas, and Panel C for Sustainable Use Areas. Columns 1–3 refer to the full sample, units inside the Arc of Deforestation, and outside it, respectively. The “Inside” coefficient represents the pre-reform discontinuity at conservation unit boundaries, while “Inside X Post-2011” captures the additional effect after the 2012 Forest Code reform. All regressions include fixed effects for PA and year, and standard errors are clustered at the PA level. **Significance levels:** ***, $p < 0.01$,

** : $p < 0.05$, * : $p < 0.1$.

Table S13: Difference-in-Discontinuities: Effects of PAs on Deforestation Before and After 2018

Panel A: Indigenous Territories			
	Full Sample	Arc of Def	Non-Arc of Def
	(1)	(2)	(3)
Inside	-0.3489*** (0.0645)	-0.5786*** (0.1102)	-0.1567*** (0.0428)
Inside X Post-2018	-0.1532* (0.0815)	-0.2262 (0.1490)	-0.1048* (0.0553)
Observations	278,315	198,794	136,642
R ²	0.06470	0.06775	0.04793
Within R ²	0.01246	0.02087	0.00603
Panel B: Strictly Protected Areas			
	Full Sample	Arc of Def	Non-Arc of Def
	(1)	(2)	(3)
Inside	-0.3286*** (0.0862)	-0.4999*** (0.1043)	-0.1738* (0.0983)
Inside X Post-2018	-0.4971*** (0.1598)	-0.2818*** (0.0731)	-0.6652** (0.2768)
Observations	118,818	61,226	52,512
R ²	0.03861	0.04439	0.03577
Within R ²	0.01487	0.01962	0.01241
Panel C: Sustainable Use Areas			
	Full Sample	Arc of Def	Non-Arc of Def
	(1)	(2)	(3)
Inside	-0.2987*** (0.0659)	-0.3516*** (0.0771)	-0.2126* (0.1092)
Inside X Post-2018	-0.7343*** (0.1793)	-0.6123*** (0.1820)	-0.8856*** (0.3134)
Observations	244,353	138,173	77,600
R ²	0.04487	0.04849	0.03363
Within R ²	0.01236	0.01149	0.01333

Notes: This table presents results from difference-in-discontinuities regressions from equation S2 where the dependent variable is the percentage change in deforestation. Panel A shows results for Indigenous Territories, Panel B for Strictly Protected Areas, and Panel C for Sustainable Use Areas. Columns 1–3 refer to the full sample, units inside the Arc of Deforestation, and outside it, respectively. The “Inside” coefficient represents the pre-reform discontinuity at conservation unit boundaries, while “Inside X Post-2018” captures the additional effect after the 2018 Bolsonaro Election. All regressions include fixed effects for PA and year, and standard errors are clustered at the PA level. **Significance levels:** ***: $p < 0.01$, **:

***: $p < 0.05$, *: $p < 0.1$.

Linear Hypothesis Testing: The Total Effect of PA Protection

The Diff-in-Disc regressions provide separate estimates for the baseline discontinuity at conservation unit boundaries and the post-period change, but they do not allow us to estimate the overall impact of protection from these coefficients alone. To address this, we perform linear hypothesis tests that sum the baseline “Inside” coefficient and the post-period interaction term, yielding the total effect of protection in each post-reform or post-election period.

Tables [S14](#) presents these total effects for ITs, SPs, and SUs, again for the full sample, arc, and non-arc sub-samples. These coefficients report the estimates presented in [Figure 4](#). The results show large and statistically significant protective effects in all post-periods, with magnitudes increasing over time and under more adverse governance conditions. The total effect sizes are largest for SPs and SUs after 2018, reflecting both a strong pre-existing discontinuity and a substantial post-Bolsonaro increase in the gap between protected and non-protected lands. These findings reinforce the main paper’s conclusion that protected areas can act as robust institutional buffers during periods of national-level environmental governance weakening.

Table S14: Total Effects from Linear Hypothesis Tests in Diff-in-Disc Models

Panel A: Indigenous Territories (ITs)							
Model	Hypothesis	Estimate	Std. Error	CI Lower	CI Upper	Wald χ^2	P-value
Post-2012	$\beta_1 + \beta_3 = 0$	-0.4099	0.0096	-0.4287	-0.3911	1825.482	0.0000
Post-2018	$\beta_1 + \beta_3 = 0$	-0.5021	0.0207	-0.5427	-0.4614	585.634	0.0000
Arc - Post-2012	$\beta_1 + \beta_3 = 0$	-0.6558	0.0145	-0.6842	-0.6274	2048.066	0.0000
Arc - Post-2018	$\beta_1 + \beta_3 = 0$	-0.8049	0.0318	-0.8671	-0.7426	642.633	0.0000
Non-Arc - Post-2012	$\beta_1 + \beta_3 = 0$	-0.2070	0.0092	-0.2249	-0.1890	509.829	0.0000
Non-Arc - Post-2018	$\beta_1 + \beta_3 = 0$	-0.2615	0.0185	-0.2978	-0.2252	199.546	0.0000
Panel B: Strictly Protected Areas (SPs)							
Post-2012	$\beta_1 + \beta_3 = 0$	-0.5362	0.0187	-0.5730	-0.4995	818.919	0.0000
Post-2018	$\beta_1 + \beta_3 = 0$	-0.8257	0.0427	-0.9095	-0.7419	373.143	0.0000
Arc - Post-2012	$\beta_1 + \beta_3 = 0$	-0.6267	0.0268	-0.6791	-0.5742	548.495	0.0000
Arc - Post-2018	$\beta_1 + \beta_3 = 0$	-0.7817	0.0572	-0.8938	-0.6696	186.739	0.0000
Non-Arc - Post-2012	$\beta_1 + \beta_3 = 0$	-0.4496	0.0262	-0.5010	-0.3981	293.436	0.0000
Non-Arc - Post-2018	$\beta_1 + \beta_3 = 0$	-0.8390	0.0635	-0.9635	-0.7145	174.352	0.0000
Panel C: Sustainable Use Areas (SUs)							
Post-2012	$\beta_1 + \beta_3 = 0$	-0.6020	0.0171	-0.6354	-0.5686	1245.418	0.0000
Post-2018	$\beta_1 + \beta_3 = 0$	-1.0330	0.0403	-1.1120	-0.9540	656.492	0.0000
Arc - Post-2012	$\beta_1 + \beta_3 = 0$	-0.5991	0.0233	-0.6449	-0.5534	658.394	0.0000
Arc - Post-2018	$\beta_1 + \beta_3 = 0$	-0.9639	0.0554	-1.0724	-0.8553	302.879	0.0000
Non-Arc - Post-2012	$\beta_1 + \beta_3 = 0$	-0.5866	0.0297	-0.6449	-0.5284	389.629	0.0000
Non-Arc - Post-2018	$\beta_1 + \beta_3 = 0$	-1.0982	0.0690	-1.2334	-0.9629	253.251	0.0000

Notes: This table reports the total effects of PA protection estimated from linear hypothesis tests that sum the baseline “Inside” coefficient and the post-period interaction term in the Difference-in-Discontinuities regressions—that is, $(\beta_1 + \beta_3)$. Panels A, B, and C correspond to Indigenous Territories (ITs), Strictly Protected Areas (SPs), and Sustainable Use Areas (SUs), respectively. Estimates are shown for the full sample, Arc of Deforestation, and non-Arc regions for the post-2012 and post-2018 periods. Wald χ^2 statistics and p-values test the null hypothesis that the total effect equals zero.

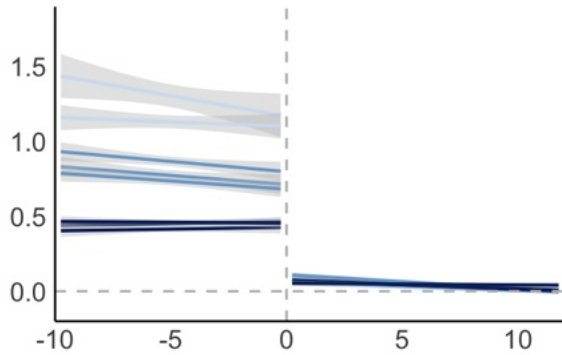
RDD Visualizations: Pre- and Post-2012 Comparison

Figure S10 plots the yearly RDD coefficients for each protection category, comparing the pre-2012 (2004–2011) and post-2012 (2012–2022) periods. The visualizations confirm the broad trends seen in the tables and are consistent with our difference-in-discontinuities results in Tables S12 and S13, which show strengthened relative protection after institutional weakening:

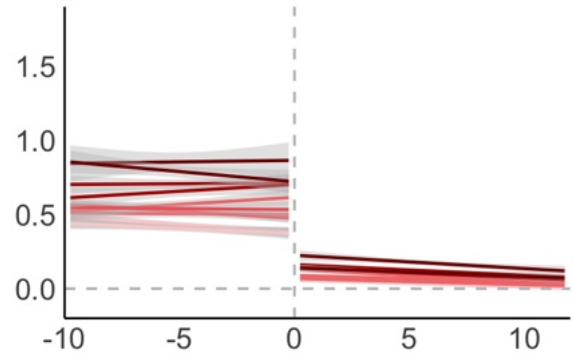
1. All three categories of protected areas show clear protective effects, with negative and often significant discontinuities in most years.
2. There is evidence of attenuation in the years around the 2012 reform, particularly in ITs and SUs, in line with the modest difference-in-discontinuities effects for that period.
3. In the post-2018 period, discontinuities become larger in magnitude, especially for SPs and SUs, reflecting a sharper contrast between protected and unprotected lands as deforestation increased outside PAs—matching the strong difference-in-discontinuities effects for Bolsonaro’s term.

These yearly RDD estimates, combined with the difference-in-discontinuities analysis, highlight both the resilience and the adaptability of protected areas as institutional buffers, particularly during periods of weakening federal environmental governance.

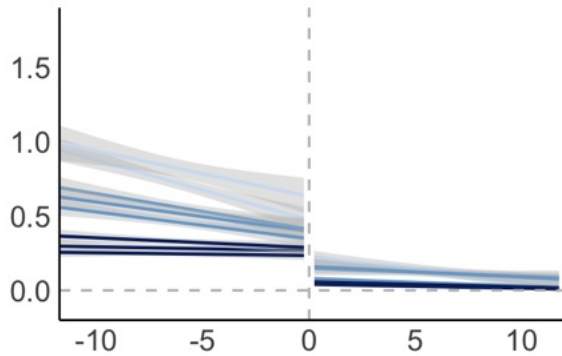
Figure S10: RDD Plots - IT, SP, and SU (12k) - Full Sample



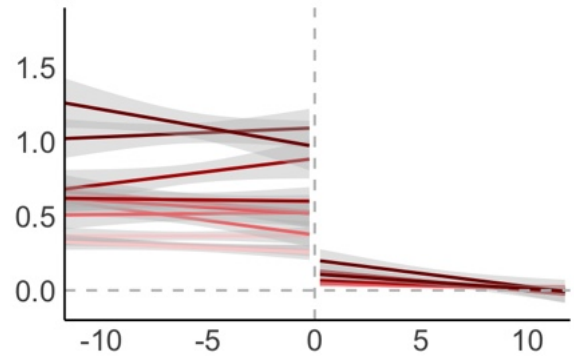
IT: Pre-2012



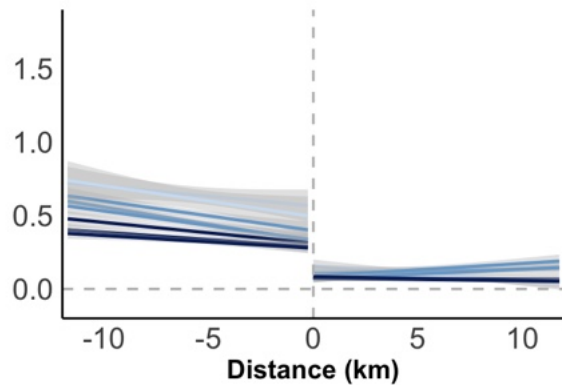
IT: Post-2012



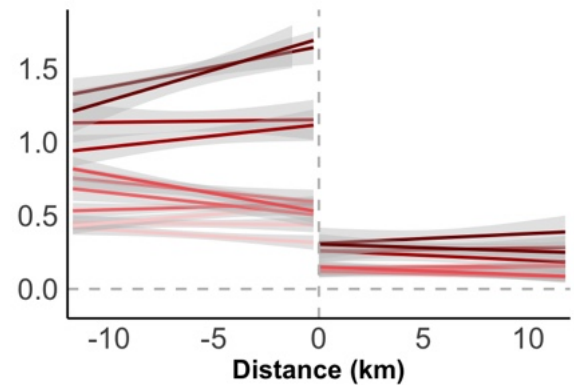
SP: Pre-2012



SP: Post-2012



SU: Pre-2012



SU: Post-2012

Year ■ 2004 ■ 2005 ■ 2006 ■ 2007 ■ 2008 ■ 2009 ■ 2010 ■ 2011 ■ 2012 ■ 2013 ■ 2014 ■ 2015 ■ 2016 ■ 2017 ■ 2018 ■ 2019 ■ 2020 ■ 2021 ■ 2022

Notes: Figure displays yearly RDD coefficient estimates for Indigenous Territories (IT, top), Strictly Protected Areas (SP, middle), and Sustainable Use Areas (SU, bottom). Each estimate uses a 12km buffer bandwidth, comparing areas inside and outside protected areas along the arc of deforestation. The left-hand plots display estimates for the 2004–2011 period (blue lines), while the right-hand plots correspond to the 2012–2022 period (red lines).

Robustness Checks

Geographic Regression Discontinuity: Different Bandwidths

To assess the robustness of our main RDD results to the choice of spatial bandwidth, we re-estimate the models using alternative bandwidths ranging from 6km to 20km around the boundaries of protected areas, instead of the baseline 12km. Figures [S11](#), [S12](#), and [S13](#) show the estimates for ITs, SPs, and SUs, respectively.

Across all bandwidth choices, the direction, magnitude, and significance of the coefficients remain highly consistent with the baseline estimates, indicating that the results are not sensitive to the specific bandwidth used. This stability supports the conclusion that the protective discontinuities observed—particularly the widening after 2012 and 2018—are robust to alternative spatial specifications

Indigenous Territories

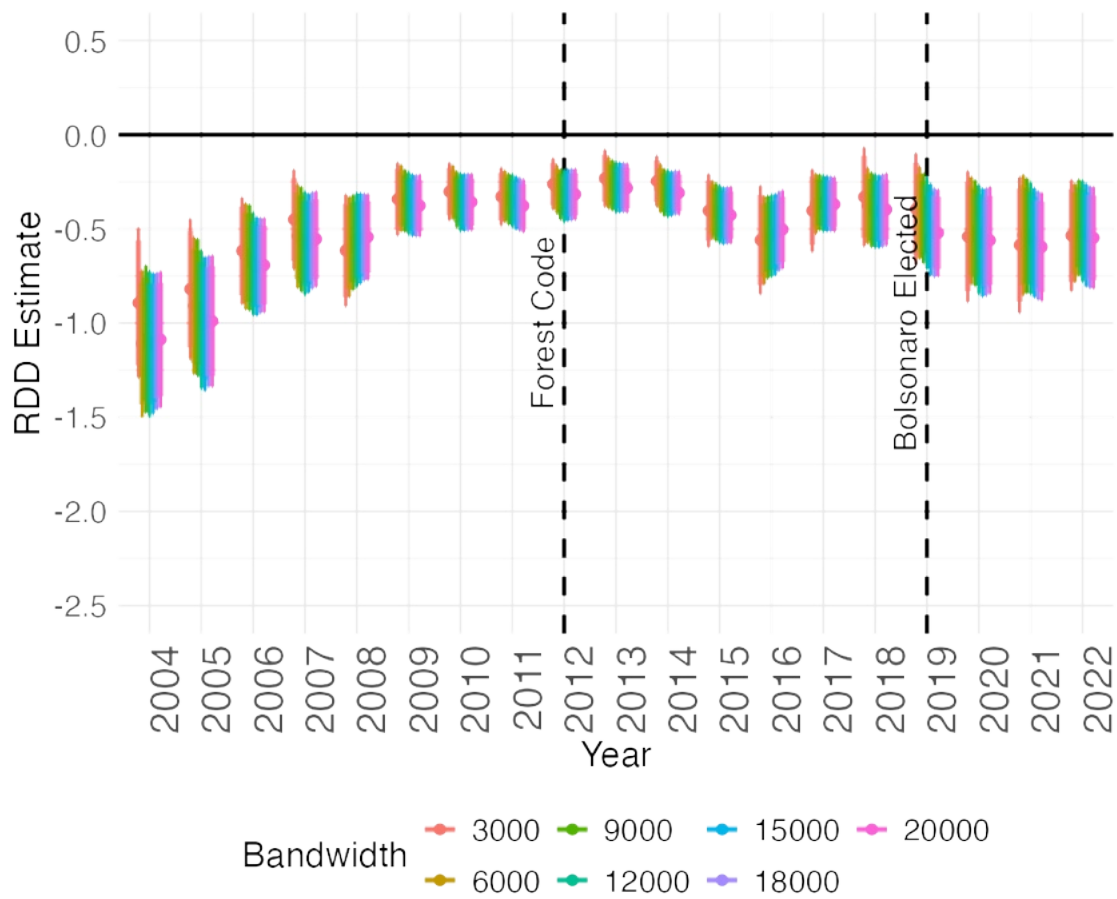


Figure S11: This figure presents the geographic regression discontinuity estimates from equation [S1](#), where the dependent variable is the percentage change in deforestation. It displays yearly RDD coefficients for Indigenous Territories (ITs), using varying buffer bandwidths (in kilometers) to compare areas inside and outside protected areas. Different colors represent estimates obtained from different bandwidth choices.

Strictly Protected Areas

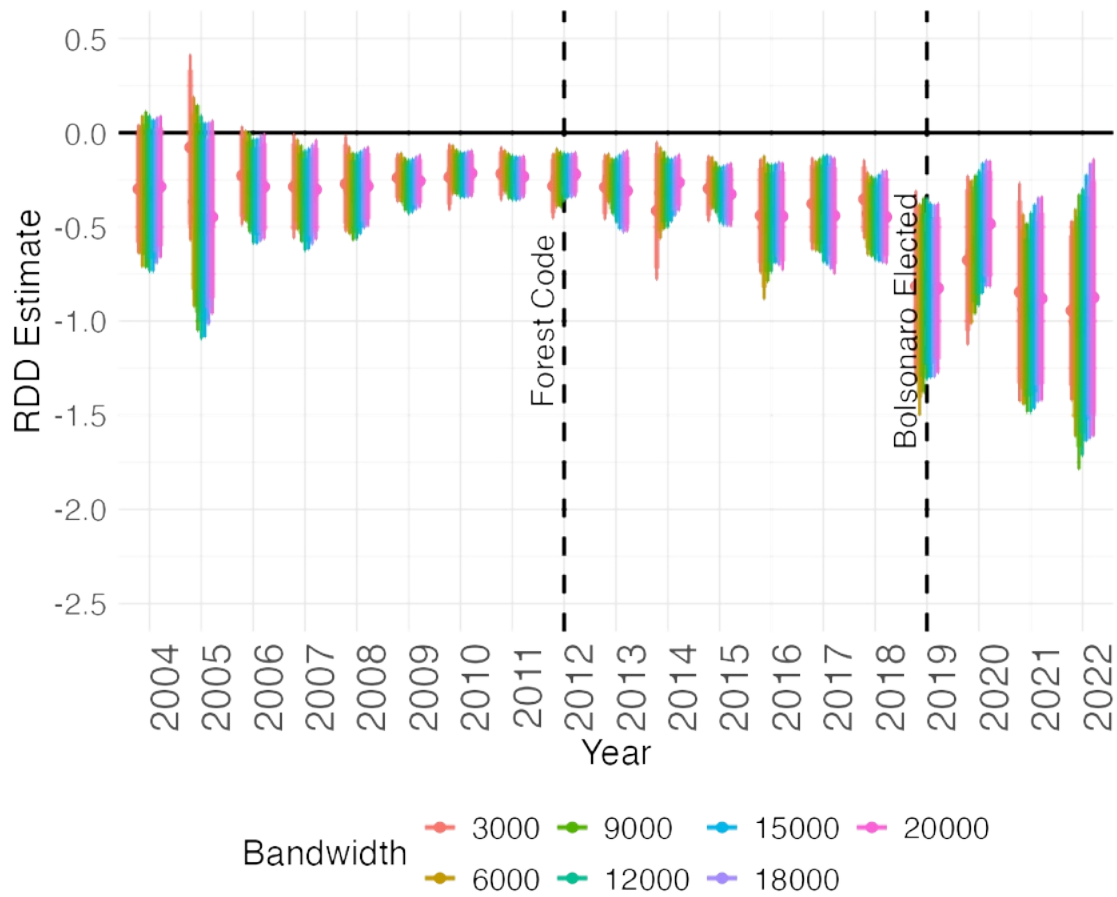


Figure S12: This figure presents the geographic regression discontinuity estimates from equation [S1](#), where the dependent variable is the percentage change in deforestation. It displays yearly RDD coefficients for Strictly Protected Areas (SPs), using varying buffer bandwidths (in kilometers) to compare areas inside and outside protected areas. Different colors represent estimates obtained from different bandwidth choices.

Sustainable Use Areas

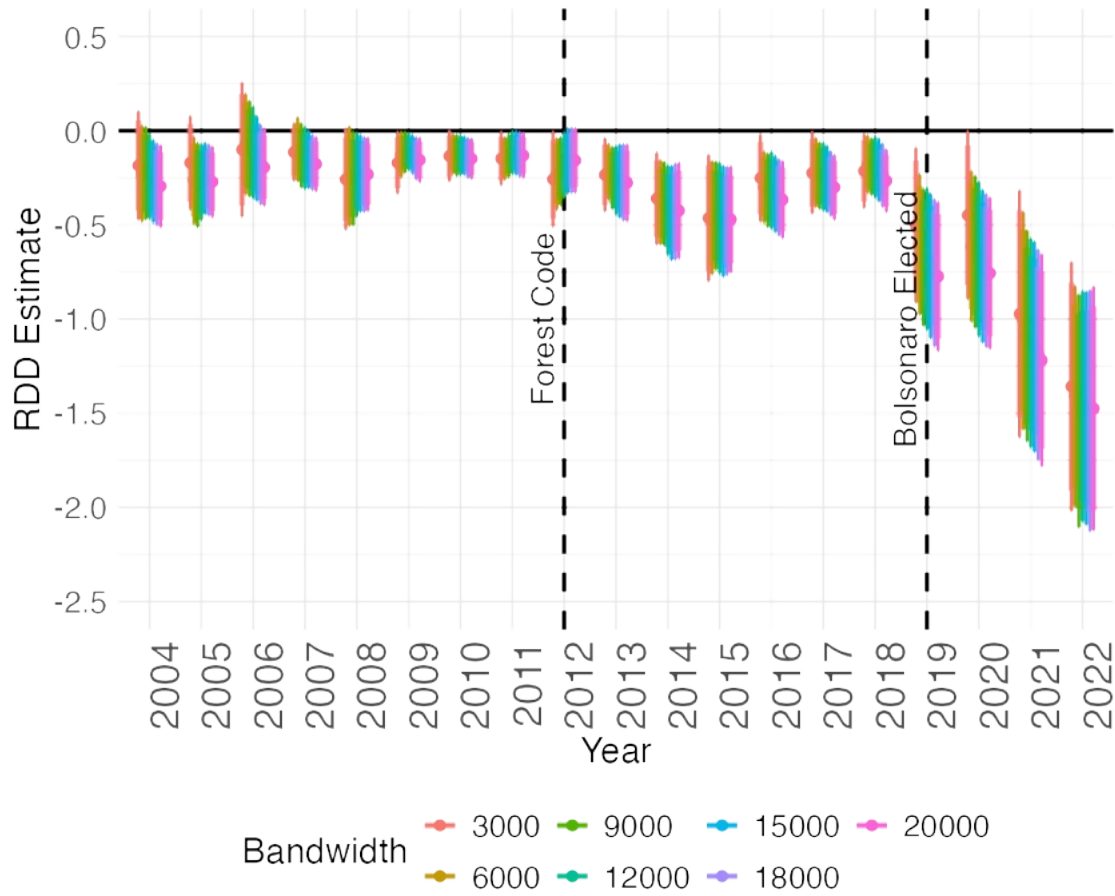


Figure S13: This figure presents the geographic regression discontinuity estimates from equation [S1](#) where the dependent variable is the percentage change in deforestation. It displays yearly RDD coefficients for Sustainable Use Areas (SUs), using varying buffer bandwidths (in kilometers) to compare areas inside and outside protected areas. Different colors represent estimates obtained from different bandwidth choices.

Balance Checks

A key assumption of the geographic RDD design is that, absent treatment, covariates should be continuous at the boundary. We assess this by plotting the relationship between each pre-treatment covariate and distance to the boundary, separately for ITs, SPs, and SUs. Negative values indicate locations outside the PA (control) and positive values indicate locations inside (treated). Figures [S14](#) [S16](#) show that covariates such as distance to cities, elevation, slope, hillshade, rivers, and roads are balanced across the boundary, with no systematic discontinuities that could confound treatment effects.

Indigenous Territories

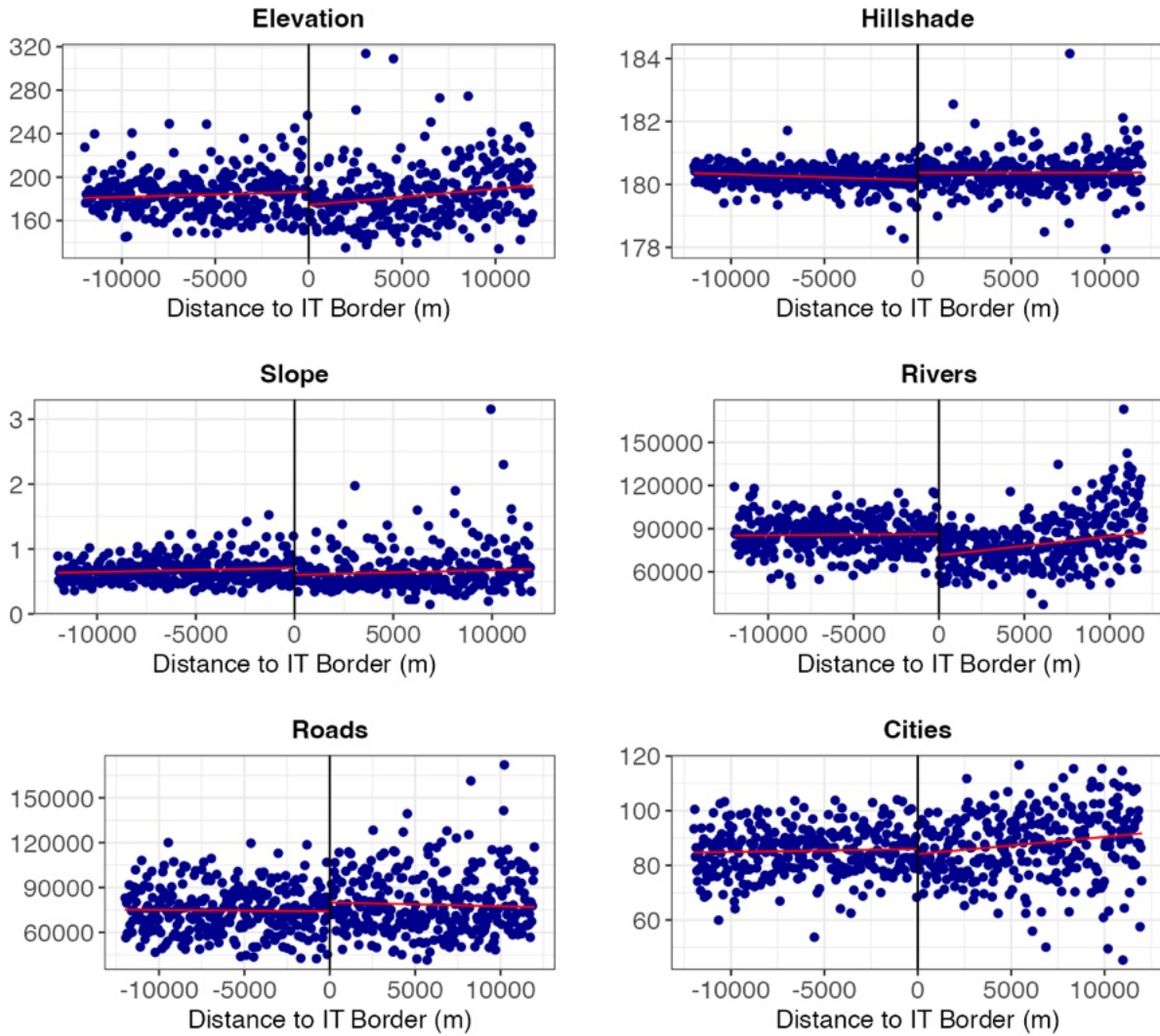


Figure S14: The figure shows pre-treatment balance for covariates within a 12km window around homologated IT boundaries. Estimates are based on the geographic regression discontinuity design described in Equation [S1](#).

Strictly Protected Areas

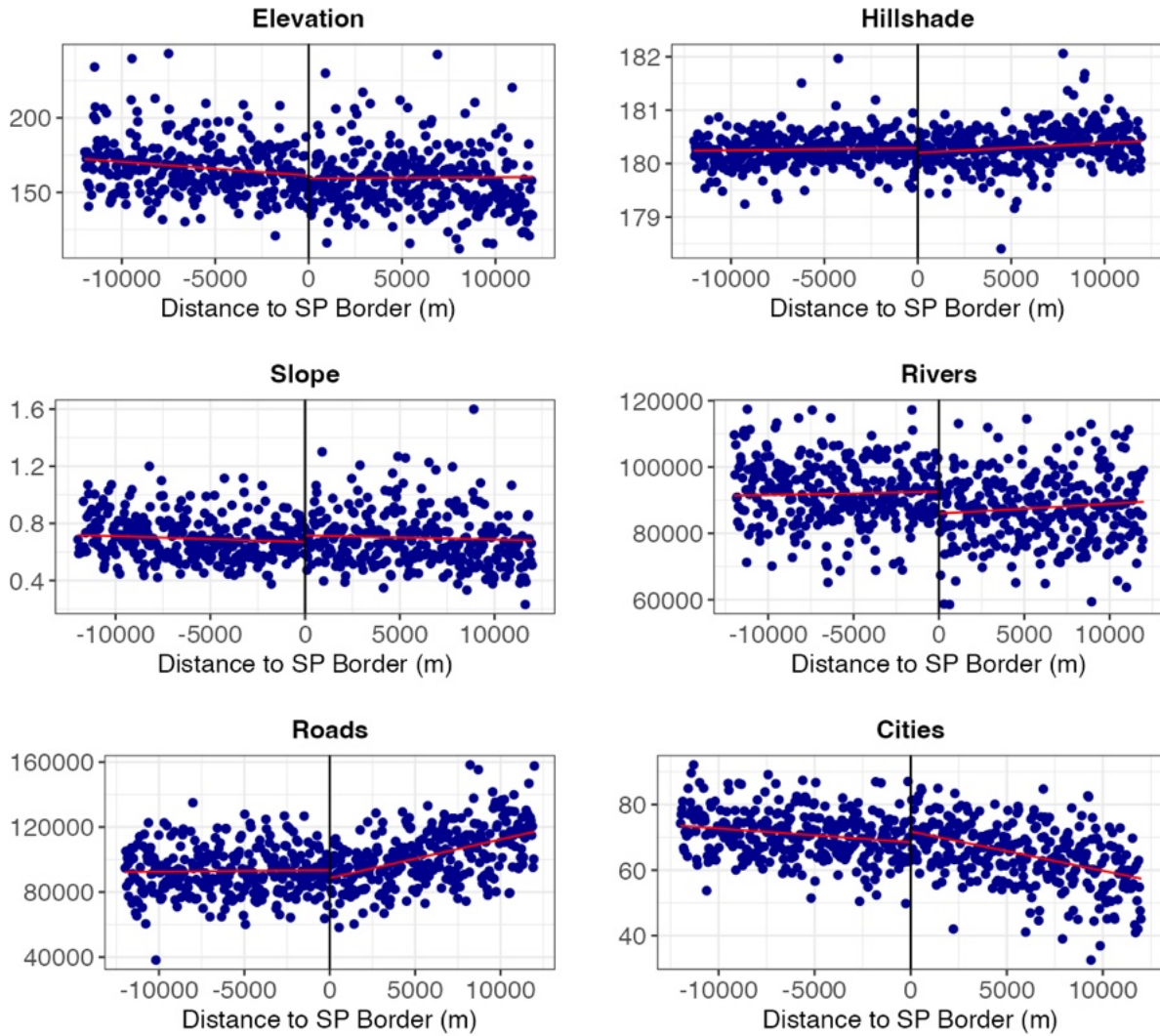


Figure S15: The figure shows pre-treatment balance for covariates within a 12km window around homologated SP boundaries. Estimates are based on the geographic regression discontinuity design described in Equation [S1](#).

Sustainable Use Areas

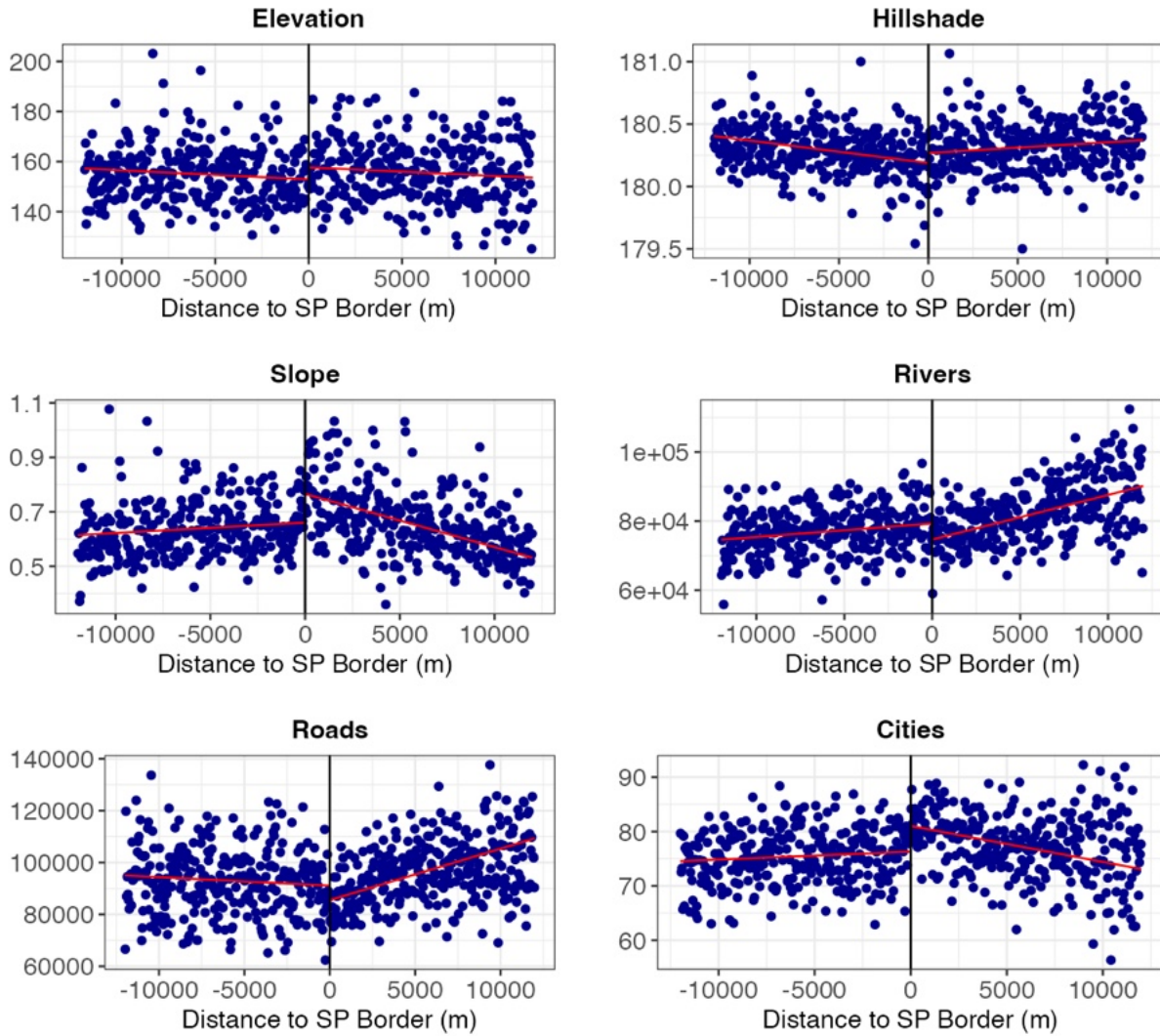


Figure S16: The figure shows pre-treatment balance for covariates within a 12km window around homologated SU boundaries. Estimates are based on the geographic regression discontinuity design described in Equation [S1](#)

Balance Test Results: Tabular Format

Table S15 presents formal regression-based balance tests, using the 12km bandwidth. For time-varying covariates (roads, cities), we include unit and year fixed effects. Consistent with the graphical results, we find no statistically significant discontinuities for most covariates. The only exception is distance to roads for ITs, which is significant at the 1% level; however, the magnitude is small relative to the average distance and is unlikely to substantially bias our results. Consistent with the balance plots (S14, S15) and S16, these tests support the validity of the RDD design and align with the robustness of our difference-in-discontinuities estimates (presented below).

Table S15: Comparison of Covariate Estimates Across ITs, SPs, and SUs (12k)

Covariate	ITs (12k)		SPs (12k)		SUs (12k)	
	Estimate	P.value	Estimate	P.value	Estimate	P.value
Hillshade	0.01	0.65	0.06	0.44	0.02	0.67
Slope	-0.03	0.28	-0.01	0.87	0.04	0.48
Elevation	3.20	0.37	-7.97	0.18	1.55	0.79
Roads	4263.62	0.00	3317.93	0.10	3739.13	0.13
Rivers	977.85	0.51	2013.43	0.26	4375.28	0.20
Cities	1091.21	0.35	-233.60	0.90	-3301.93	0.31
N	1,673,985		519,878		919,049	

Placebo Threshold Tests

We also re-estimate our regression discontinuity at artificial cut-off points located ± 2 and ± 5 km from the actual PA boundaries. Since no policy discontinuity exists at these placebo boundaries, any significant effects would suggest potential bias from spatial trends rather than treatment. Figure [S17](#) confirms that the estimates at the placebo cut-offs are not different from zero, suggesting that our main results are not driven by such spatial biases.

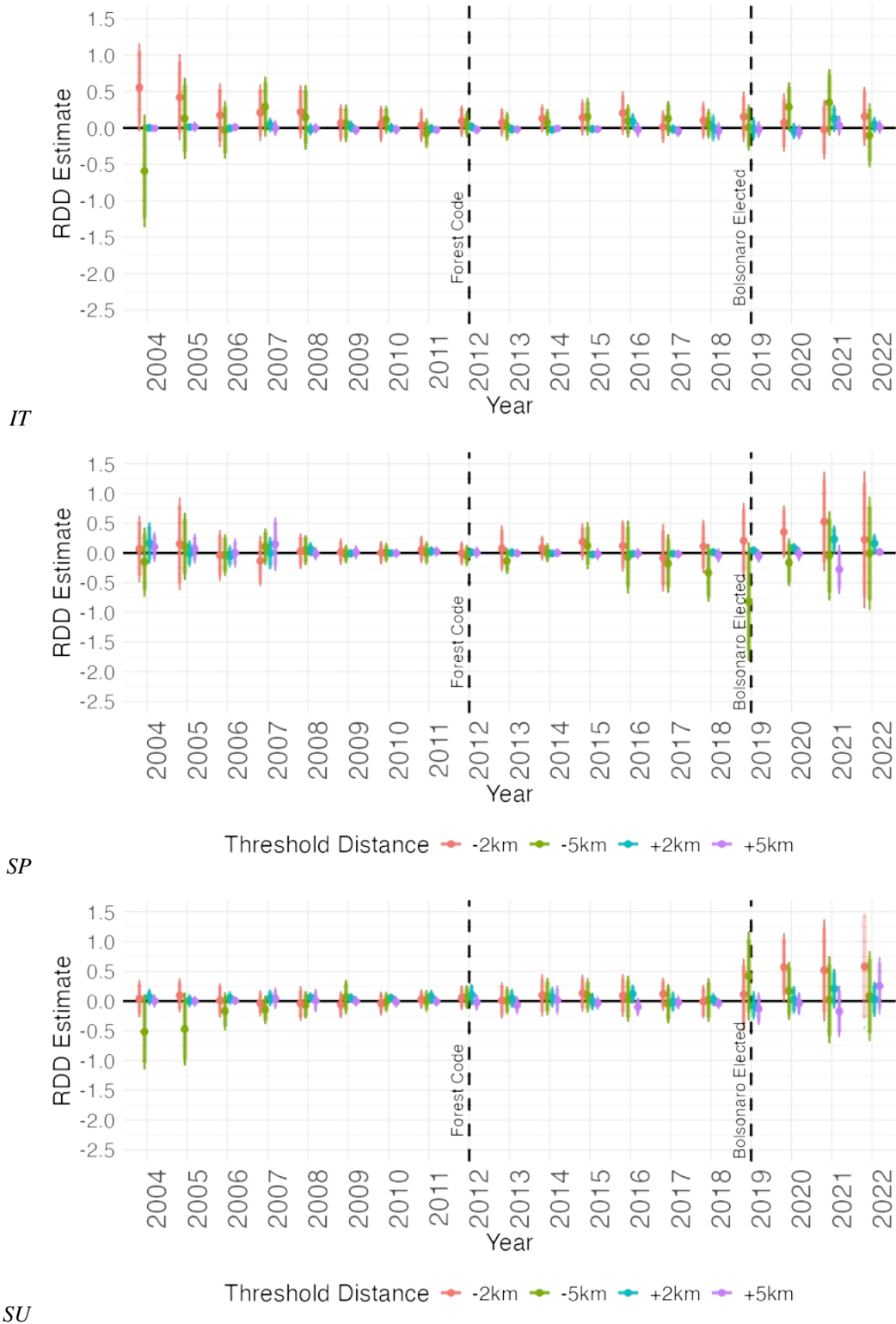


Figure S17: This figure presents geographic regression discontinuity estimates from equation [S1](#) where the dependent variable is the percentage change in deforestation. The figure shows RDD estimates at placebo cut-offs for Indigenous Territories (ITs), Strictly Protected Areas (SPs), and Sustainable Use Areas (SUs). Each panel displays estimates within $\pm 2\text{km}$ and $\pm 5\text{km}$ of artificial boundaries set around the actual PA boundaries.

Pre-Reform Trends

Finally, we verify the parallel trends assumption for our difference-in-discontinuities design by examining pre-2012 deforestation trajectories inside and outside each PA type. Figure S18 plots *average* annual deforestation rates from 2009–2013, distinguishing between pre- and post-reform years. We focus on the three years prior to 2012, as they provide the most reliable assessment of pre-trends given that deforestation dynamics can vary substantially over time. Overall, the figure indicates that the parallel trends assumption largely holds, with only Strictly Protected Areas showing a small pre-treatment deviation.

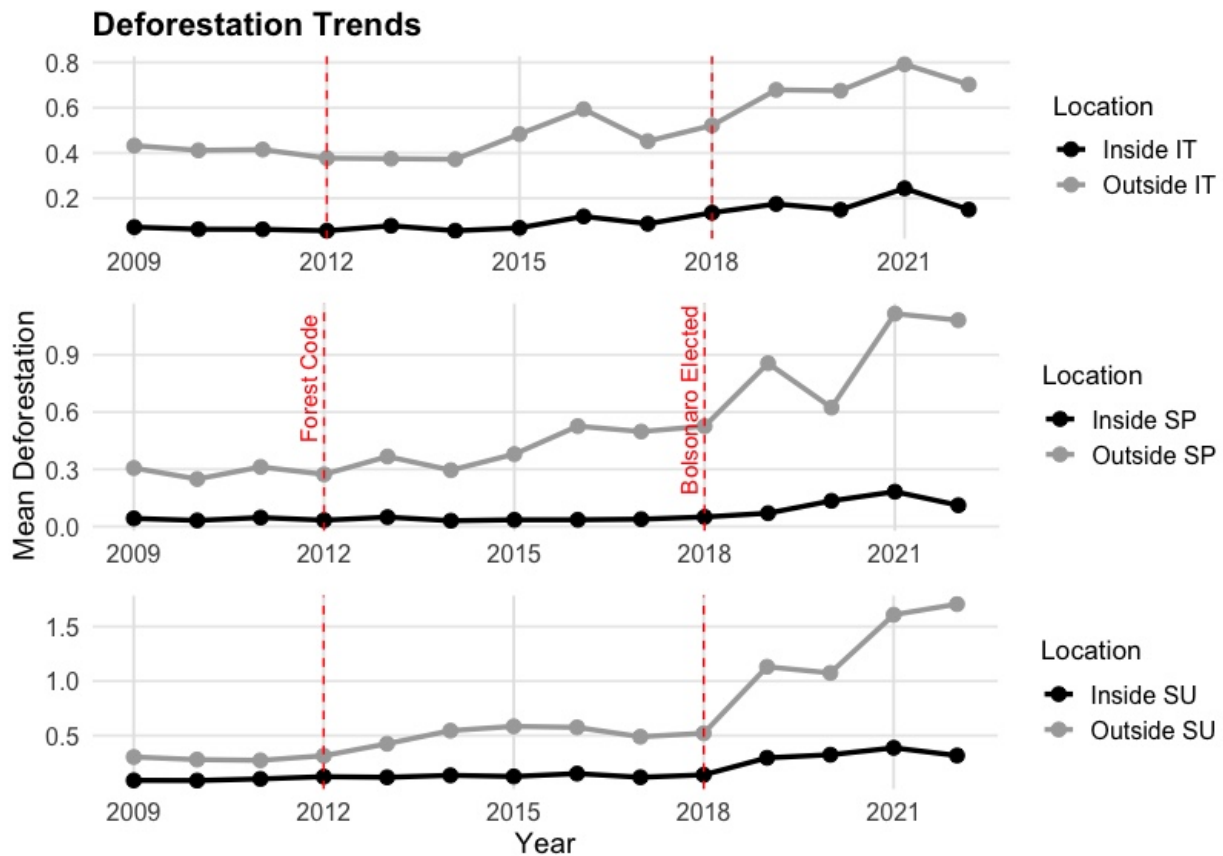


Figure S18: Average annual deforestation rates inside and outside protected areas, 2009–2022. Each panel reports mean deforestation trends for one type of protected area—Indigenous Territories, Sustainable Use, and Strictly Protected—distinguishing between areas located inside (solid line) and outside (dashed line) the protection boundaries. Dashed vertical red lines mark key policy moments: the 2012 Forest Code reform and the 2018 election of Jair Bolsonaro

Cost-Benefit Analysis of Remote Protected Area Designation

This analysis demonstrates that even under conservative assumptions, the social benefits of carbon retention vastly exceed the private opportunity costs of foregone agricultural development.

Opportunity Costs of Protection

The opportunity cost of designating land as protected represents the forgone private economic value from alternative uses, primarily cattle ranching in the Amazon context. Bowman et al. (2012) (58) provide spatial estimates of the net present value (NPV) of converting forest to pasture across the Brazilian Amazon, accounting for establishment costs, ongoing management expenses, cattle productivity, market prices, and transportation costs to urban markets. Their highest estimated 30-year NPV reaches approximately US\$700 per hectare in the most accessible and productive locations—areas with good road access, proximity to markets, and favorable biophysical conditions for pasture.

However, the protected areas that demonstrated latent conservation value in our analysis are predominantly located in remote frontier regions far from existing infrastructure and markets. In these areas, the economics of cattle ranching are fundamentally different. High transportation costs substantially reduce the net returns from selling cattle, while distance from input markets increases the costs of establishing and maintaining pasture. Bowman et al. (2012) show that NPV declines sharply with distance from roads and markets, falling to zero or becoming negative in many remote locations. For the remote protected areas in our sample—characterized by poor market access, limited infrastructure, and high transportation costs—the opportunity cost of designation was therefore minimal to negligible at the time these areas were established.

Furthermore, many of these protected areas were designated on undesignated public forest lands rather than on privately held properties. This substantially reduced the direct costs of designation, as the government did not need to expropriate land or compensate existing owners. The primary cost was therefore the administrative expense of designation and demarcation.

Social Benefits from Carbon Retention

The social benefits of protecting Amazon forests stem primarily from avoided greenhouse gas emissions, though forests also provide other valuable ecosystem services including biodiversity conservation, water cycling, and cultural values for Indigenous peoples. Here we focus on carbon benefits, which can be quantified with reasonable precision using established methods.

Intact Amazon forests store roughly 150–250 tonnes of carbon per hectare (tC/ha) in above- and below-ground biomass (59, 60). Converting forest to pasture releases most of this carbon to the atmosphere as CO₂, either through burning or decomposition. To convert carbon storage to CO₂ equivalents, we multiply by the molecular weight ratio of CO₂ to C (44/12 = 3.67), yielding 550–920 tonnes of CO₂ per hectare (tCO₂/ha).

The social cost of carbon (SCC) represents the present-value economic damages from emitting one additional tonne of CO₂, accounting for impacts on agricultural productivity, human health, flood risk, ecosystem services, and other climate-related damages. Recent estimates by Rennert et al. (2022) (84), which update earlier U.S. government estimates using improved climate models and damage functions, place the SCC at approximately US\$185 per tCO₂ using a 2% discount rate. The U.S. Environmental Protection Agency (2023) (85) has adopted similar values in its regulatory impact analyses. More conservative estimates, using higher discount rates or more limited damage functions, yield SCC values around US\$50 per tCO₂.

Multiplying forest carbon storage by the social cost of carbon yields the avoided-emissions benefit of protection. Using the lower bound of forest carbon storage (550 tCO₂/ha) and the conservative SCC estimate (US\$50/tCO₂), we obtain:

$$550 \text{ tCO}_2/\text{ha} \times \text{US\$}50/\text{tCO}_2 = \text{US\$}27,500/\text{ha}$$

Using the upper bound of carbon storage (920 tCO₂/ha) and the higher SCC estimate (US\$185/tCO₂):

$$920 \text{ tCO}_2/\text{ha} \times \text{US\$}185/\text{tCO}_2 = \text{US\$}170,200/\text{ha}$$

Thus, the avoided-emissions value of keeping one hectare of remote Amazon forest protected ranges from approximately US\$27,500 to US\$170,200, with a midpoint estimate around US\$80,000/ha.

Benefit-Cost Ratios

Comparing these social benefits to the opportunity costs reveals strongly favorable benefit-cost ratios. Even using the most conservative carbon valuation (US\$27,500/ha) against the highest agricultural returns in accessible locations (US\$700/ha), the benefit-cost ratio exceeds 39:1. For the remote protected areas in our sample, where agricultural opportunity costs are near zero, this ratio would be substantially higher or effectively infinite where agricultural NPV is negative.

Using midpoint estimates—carbon benefits of US\$80,000/ha and opportunity costs well below US\$700/ha in remote locations—yields benefit-cost ratios exceeding 100:1. With the higher SCC estimate (US\$170,200/ha), ratios approach or exceed 200:1.

These calculations account only for carbon benefits and exclude other important ecosystem services. Including the value of biodiversity conservation, water cycling services, non-timber forest products, and cultural values would further increase the social benefits of protection. The analysis also does not account for the option value of preservation under uncertainty, as formalized by Arrow and Fisher (1974). Given irreversible forest loss and uncertainty about future benefits (including potential pharmaceutical discoveries, climate regulation services, and non-use values), economic theory suggests that preservation generates additional option value beyond the direct use and carbon benefits quantified here.

In summary, the designation of protected areas in remote Amazon regions delivered enormous social benefits relative to minimal private opportunity costs. This favorable cost-benefit profile meant that these areas could be established efficiently and at low political cost, while simultaneously creating institutional anchors that proved crucial when governance subsequently weakened and deforestation pressures expanded into previously remote regions.