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Protected area types, strategies and impacts in Brazil's Amazon: public protected area strategies do not yield a consistent ranking of protected area types by impact

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The leading policy to conserve forest is protected areas (PAs). Yet, PAs are not a single tool: land users and uses vary by PA type; and public PA strategies vary in the extent of each type and in the determinants of impact for each type, i.e. siting and internal deforestation. Further, across regions and time, strategies respond to pressures (deforestation and political). We estimate deforestation impacts of PA types for a critical frontier, the Brazilian Amazon. We separate regions and time periods that differ in their deforestation and political pressures and document considerable variation in PA strategies across regions, time periods and types. The siting of PAs varies across regions. For example, all else being equal, PAs in the arc of deforestation are relatively far from non-forest, while in other states they are relatively near. Internal deforestation varies across time periods, e.g. it is more similar across the PA types for PAs after 2000. By contrast, after 2000, PA extent is less similar across PA types with little non-indigenous area created inside the arc. PA strategies generate a range of impacts for PA types—always far higher within the arc—but not a consistent ranking of PA types by impact.

1. Introduction

It is important to understand how circumstances affect the forest impact of protected areas (PAs). Roles for tropical forest in both species habitat and carbon storage motivate consideration of how global actors can support provision of forest's public goods. PAs are part of the strategy (e.g. see the Convention on Biological Diversity work program (cbd.int)), yet resources for PAs are scarce so resource allocations for PAs must be efficient. Further, if richer countries purchase reductions in deforestation to offset their emissions, they should demand that those reductions be credible. Thus, evidence about when PAs will avoid deforestation, and by how much, is highly relevant. For one critical forest frontier, this paper studies deforestation impacts by PA type. In particular, we show that variations in public strategies prevent a consistent ranking of PA types by impact.

For studying impacts, we must emphasize that forest in a PA may not indicate an impact. If forest would have remained pristine without any policy, then the PA did not make a difference. Thus, without knowing the baselines, we cannot correctly estimate significant impacts from PAs. Furthermore, true PA impact, and thus also quality estimates, will vary greatly across landscapes. For perfect enforcement, for instance, impact varies with level of deforestation pressure blocked. This holds, not just in theory, but also in practice, as shown in recent studies of other countries.[1]

We study the Brazilian Amazon, an enormous forest frontier and a developing landscape. Investments in development (e.g. roads) and conservation (e.g. PAs) have been considerable—and the fate of most of this forest remains to be

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determined. We evaluate deforestation impacts during 2000–2004 and 2004–2008 owing to the earlier Brazilian Amazon PAs established pre-2000, as well as the impact upon 2004–2008 deforestation of newer PAs established during 2000–2004. Such study extends limited prior literatures on PA impacts across the whole Brazilian Amazon. Research with leading results includes [5], applying multiple methods[2] to estimate the average impacts for types of PAs, and [7] using matching to estimate the average impact for all PAs and then for subsets based upon drivers of deforestation (which also are likely to affect public choices). The latter finds higher impacts for PAs closer to roads and cities, and that regions vary in impact by an order of magnitude. Here, we exploit variation by region and time period to study PA types.

Such analyses also extend existing literature about variations in impacts across PA types. Previously, in analysing over 100 countries [4] show that, on average, siting differs by PA type: stricter PAs are more likely to be biased away from deforestation pressures. Using fire frequency as an outcome, Nelson & Chomitz [8] extend such global examination, finding that multiple-use PAs reduce fire more than do strict PAs. This suggests that types' rules alone do not always dominate impacts. However, global studies also explicitly promote closer studies of PA types in specific countries because average strategies do not hold in all countries and, more generally, impacts will vary.

Moving to specific countries, Ferraro *et al*. [9] examine impacts of PA types in Bolivia, Costa Rica, Indonesia and Thailand. Across those countries, on average, strict PAs avoid more deforestation, though the gap can be small. These authors emphasize that PA impacts involve multiple choices. Such prior work motivates our novel documentation of variations in PA strategies and impacts.

Other research [10] studies one Brazilian state, Acre, outside 'the arc of deforestation'. There, multiple-use PAs that allow internal smallholder deforestation are sited closer to pressure, perhaps owing to political 'good will' that permits such PAs even though they reduce deforestation. This yields more forest impact, on net, than in stricter PAs, despite greater internal deforestation. In comparison, below we show the opposite, on average, for the states in the arc of deforestation.

We examine regions and time periods with differing deforestation and political pressures. We start by separating 'In The Arc' (Rondonia, Mato Grosso, Para, Maranhao, Tocantins) from 'Not In Arc' (Acre, Amazonas, Roraima, Amapa) states (figure 1). Reflecting points in [5] about the use of non-PA policies (forest code, enforcement, federal blacklist, local responses), as well as a fall in deforestation rates around 2004, in addition we separate time periods. We split 2000–2008 into 2000–2004 and 2004–2008 and analyse deforestation impacts of PA types for those periods.[3]

To infer any deforestation impact, we use unprotected outcomes to estimate a 'baseline', i.e. what would have happened to the protected lands without a PA.[4] Baselines are challenging: using all unprotected lands is wrong if PA siting is biased; and lands near PAs risk contamination by local spillovers. Siting biases towards pressures arise if planners target impact (e.g. [17]), yet biases away from pressures can arise from cost avoidance (Joppa & Pfaff [3] find this more common globally), as land prices and political costs likely rise with profits from and thus pressure for deforestation.

We focus not on average impacts across PA systems but, instead, impacts of PA types and their variations across regions and time periods. Brazilian Amazon PAs have distinct goals. The less restrictive types are 'sustainable use' (IUCN V-VI[5]), which brings to mind local needs, as well as 'Indigenous' lands (no IUCN bin exists for this type), which refers to less empowered peoples. Those two categories of PAs can be compared with 'Integral' protection (IUCN's I-IV), which is more restrictive, officially not permitting any production or deforestation.[6] Both the sustainable use and Indigenous types are linked with local stakeholders, though the Indigenous lands may be more spatially constrained, e.g. requiring long-standing, specific past populations. That restricts siting and perhaps extent for Indigenous lands that also may vary in enforcement.

The paper proceeds as follows. Section 2 describes data and methods. Section 3 presents impacts by type, region and period. Section 4 discusses our results and their implications.

2. Data and methods

(a) Dependent and independent variables

(i) Deforestation

We study deforestation in both 2000–2004 and 2004–2008 using PRODES data on land cover for 2000, 2004 and 2008 from INPE (*Instituto Nacional de Pesquisas Espaciais*).[7] For a single pixel, the data indicate one land-cover class. Thus, deforestation is a change from forest to a non-forest land cover. For each forest pixel in 2000, our deforestation variable is binary (value = 1 if forest in 2000 but not 2004, and value = 0 if it is forest in both years); and for each forest pixel in 2004, again deforestation is binary (value 1 if forest in 2004 but not 2008, and 0 if forest in both years).

The PRODES data were downloaded in raster format from INPE's website (see http://www.inpe.br/ingles/) in Geographic Coordinate System, South American Datum of 1969. The cell resolution was 0.000808 decimal degrees, equivalent to 2.9088 s or 90 m around the equator once projected. INPE's own analyses, since 2001, are conducted at finer resolution. To create these pixels, they resampled to 90 × 90 m.

(ii) Protected areas

The Brazilian Legal Amazon contains 521 742 300 ha (i.e. about 5 million km^2). We provide facts for all PAs (see also [7]) but principally examine the PAs within two groups (figure 1): 'In The Arc' (Rondonia, Mato Grosso, Para, Maranhao, Tocantins); otherwise, 'Not In Arc' (Acre, Amazonas, Roraima, Amapa). Many PAs, including a majority of Indigenous lands, were created in 1990–1999. Others were created during 2000–2004, the second batch of PA creation that we study.

We consider a pixel to be 'protected' if the PA it is in was created before the deforestation being analysed. Thus for 2000–2004 deforestation, we can study impacts only for PAs created before 2000. However, for 2004–2008 deforestation, we can consider the impacts also of PAs created during 2000–2004. Pixels found in PAs created during the period of deforestation simply are not included in those analyses, as we cannot tell whether deforestation preceded them or not.

(iii) Relevant characteristics

Many factors are expected to affect deforestation because they influence its benefits and its costs. Because net benefits of clearing may raise land prices, and also local resistance to

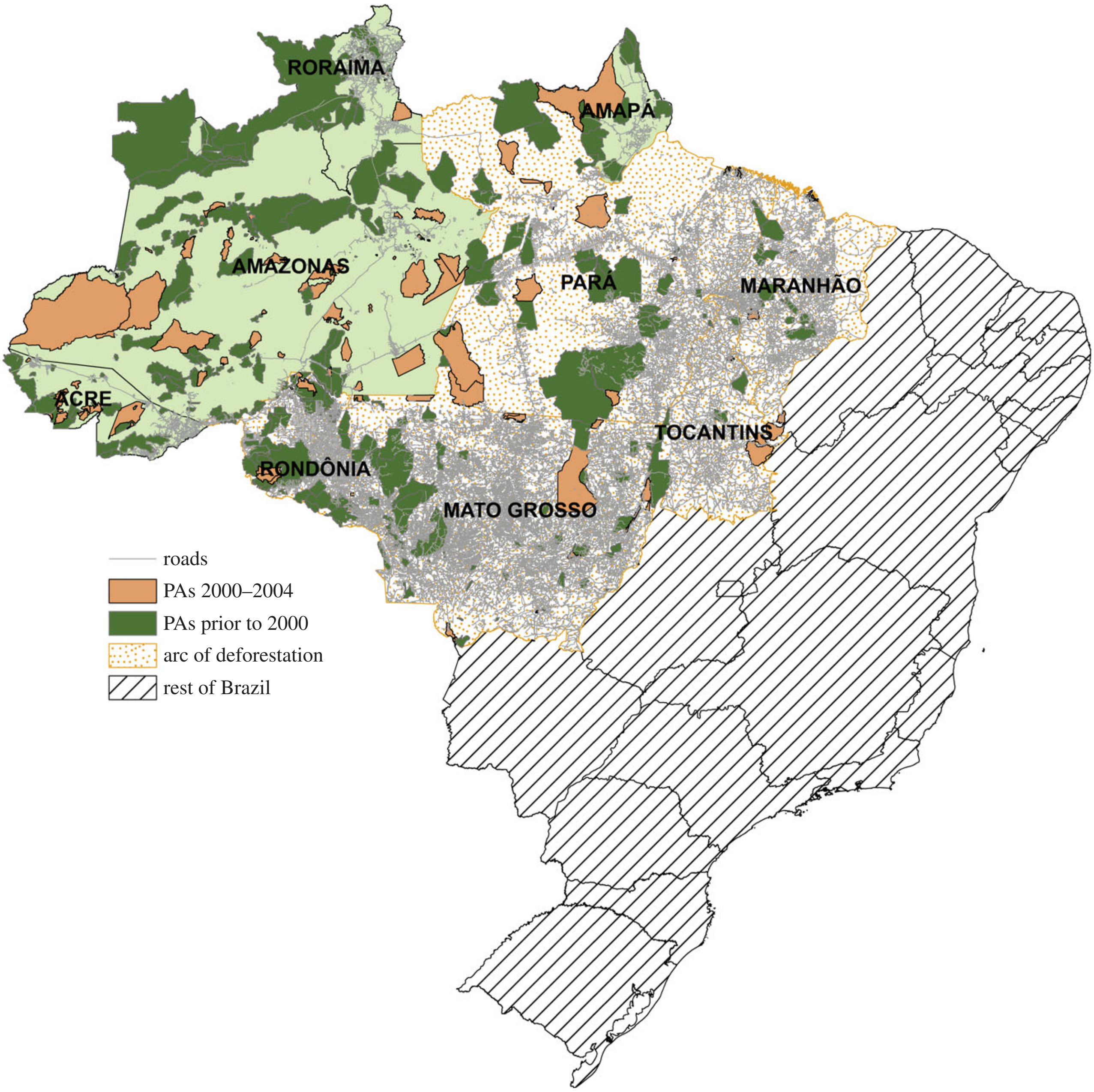

Figure 1. Brazil, The Legal Amazon, The Arc of Deforestation and PAs. The Legal Amazon region includes northern Mato Grosso and western Tocantins and Maranhão, along with the entirety of these states: Acre, Rondonia, Pará, Amazonas, Roraima and Amapá. Of those, our 'arc of deforestation' designation has been used for Rondonia, Mato Grosso, Para, Maranhao and Tocantins—implying that 'not in arc' is Acre, Amazonas, Roraima and Amapá. (Online version in colour.)

creating PAs, those same factors may affect PA siting. This can bias estimates of PAs' deforestation impacts.

We want to control for the influences of factors we observe that affect the profitability of deforestation. This includes the distance to the nearest road (in 1985, before most protection), as well as distance to the nearest big city in 1991 (the date again chosen to come before protection). Digital road maps were provided by the Department of Geography at Michigan State University, based on paper maps by DNER (*Departamento Nacional de Estradas de Rodagem*), an agency in the Transport Ministry in Brazil, while the data on 1991 cities are from the Demographic Census. We also employ a soil quality index, rainfall [19], vegetation type (cerrado versus not), as well as a binary indicator of slope (one that distinguishes, e.g. 'steeply sloped' from 'rolling hills') extracted from the 'Diagnostico' data of IBGE (*Instituto Brasileiro de Geografia e Estatistica*).

(iv) Pixel sample and basic relationships

We start with a sample of 800 000 pixels, drawn randomly from across the Brazilian Amazon—implying one sample pixel for every 650 ha (more than 6 km^2), a good but not extremely dense coverage. If land-cover information (16 categories) does not clearly indicate forest at the start of a period, we drop the pixel (including *No Data*, *Non-Forest*, *Water*, *Clouds* and *Residual*). That leaves us with a sample of about 450 000 pixels in forest to examine for deforestation from 2000 forward.

Table 1 shows that deforestation rates and protection, as well as key pixel characteristics, vary considerably across space and time. Regression results in tables 2 and 3 (probits for binary protection and deforestation outcomes) confirm expected underlying patterns, e.g. deforestation being lower but protection being higher when moving to pixels farther from roads and big cities. Regressions show variation over

Table 1. Comparing deforestation rates and deforestation-relevant pixel characteristics. Entries are means for row samples.

in 2000	# pixels in row's sample	2000–2004 deforest rate (%)	road distance (km)	big city distance (km)	rain index (mm)	vegetation indicator (binary)	soil fertility (categ. 1 to 5)	slope index (% flat)	forest edge distance (km)	river distance (km)
unprotected	328 779	5.52	90	361	2300	0.04	3.03	0.60	3.48	21.23
arc	161 985	10.39	59	351	2085	0.08	3.16	0.60	2.32	22.07
no-arc	166 794	0.80	121	371	2507	0.01	2.91	0.01	4.60	20.41
pre-2000 PAs	124 269	0.61	115	418	2333	0.04	2.99	0.57	4.02	26.51
arc	57 300	1.16	89	374	2008	0.07	3.18	0.61	4.01	25.50
indigenous land	41 186	0.75	104	420	1992	0.09	3.18	0.61	3.86	25.72
sustainable use	10 925	2.49	45	230	2062	0.01	3.28	0.67	3.64	22.25
integral protection	5189	1.66	54	307	2026	0.08	3.04	0.56	6.00	30.61
no-arc	66 969	0.13	137	456	2611	0.01	2.83	0.54	4.03	27.38
indigenous land	41 154	0.14	115	493	2603	0.01	2.70	0.56	4.17	25.76
sustainable use	15 080	0.15	192	372	2543	0.01	3.25	0.48	4.52	31.46
integral protection	10 736	0.10	142	431	2736	0.00	2.72	0.55	2.84	27.85
in 2004	# pixels in row's sample	2004–2008 deforest rate (%)	road distance (km)	big city distance (km)	rain index (mm)	vegetation indicator (binary)	soil fertility (categ. 1 to 5)	slope index (% flat)	forest edge distance (km)	river distance (km)
unprotected	279 447	3.82	90	361	2312	0.05	3.06	0.58	3.29	21.14
arc	130 808	7.44	55	349	2089	0.08	3.22	0.58	2.12	21.78
no-arc	148 639	0.64	122	373	2508	0.01	2.93	0.58	4.32	20.57
pre-2000 PAs	122 564	0.46	115	419	2334	0.04	2.99	0.57	4.03	26.59
arc	56 445	0.92	89	374	2007	0.08	3.18	0.61	4.05	25.47
indigenous land	40 877	0.16	105	421	1993	0.09	3.18	0.61	3.88	25.64
sustainable use	10 653	3.74	46	229	2065	0.01	3.27	0.67	3.69	22.04
integral protection	4915	1.18	51	298	2005	0.08	3.02	0.56	6.16	31.50
no-arc	66 119	0.07	137	458	2612	0.01	2.83	0.54	4.01	27.55
indigenous land	40 668	0.03	115	494	2601	0.01	2.70	0.56	4.14	25.82
sustainable use	15 049	0.19	192	372	2544	0.01	3.25	0.48	4.52	31.49
integral protection	10 402	0.03	144	440	2746	0.00	2.73	0.55	2.77	28.57

(*Continued*.)

Table 1. (*Continued.*)

in 2004	# pixels in row's sample	2004–2008 deforest rate (%)	road distance (km)	big city distance (km)	rain index (mm)	vegetation indicator (binary)	soil fertility (categ. 1 to 5)	slope index (% flat)	forest edge distance (km)	river distance (km)
2000–2004 PAs	36 282	0.07	128	495	2489	0.02	3.20	0.34	5.27	19.89
arc	7306	0.22	100	482	2080	0.11	3.00	0.73	3.58	17.03
indigenous land	5957	0.24	110	504	2081	0.08	3.00	0.73	3.55	16.45
sustainable use	594	0.00	54	227	1864	0.02	3.17	0.66	4.03	31.35
integral protection	755	0.26	59	514	2248	0.41	2.83	0.74	3.49	10.37
no-arc	28 976	0.03	135	498	2592	0.00	3.26	0.25	5.69	20.61
indigenous land	15 264	0.02	128	589	2649	0.00	3.27	0.22	6.58	17.31
sustainable use	9505	0.07	158	435	2595	0.00	3.08	0.37	6.55	22.39
integral protection	4207	0.00	111	310	2378	0.00	3.62	0.09	0.51	28.56

space and time, e.g. differences by state in deforestation and in protection, for each region and period, plus across-period shifts even in the signs of state effects.

(b) Matching approach

If PAs in the Brazilian Amazon had been implemented randomly across all of the forested pixels, then their deforestation impacts would be easy to estimate. We would need only the differences between the deforestation rates inside versus outside of the PAs. The deforestation rates outside would be unbiased estimates of what would have happened, without PAs, to deforestation inside (as the influences of key factors other than PAs would be the same owing to the randomization).

However, PAs do not appear to have been located in a 'random-like' fashion. Of course, we know they were not actually randomly sited, in the sense of flipping coins or throwing darts. Yet, a key question is whether there are any biases along dimensions that influence deforestation. Tables 1 and 2 show that relevant pixel characteristics—including the road and city distances—of the forest pixels in the PAs in the Amazon differ from those of forested pixels outside of PAs. Further, as land-use theory suggests and table 3 confirms, road and city distances affect the rates of deforestation. Thus, observed differences in deforestation rates between PAs and unprotected pixels reflect not only PA impacts but also the influences of differences in pixel characteristics.

To reduce those influences, we use matching techniques. The idea is to find an improved control group by matching each protected pixel with—and then comparing to—the most similar unprotected pixels, for more of an 'apples-to-apples' comparison. Similarity must be defined. Within propensity-score matching, pixels with the most similar probabilities of being PA sites are chosen for comparison with PA pixels. From regressions in table 2, we predict each pixel's probability of being protected (its 'propensity'), given its characteristics, then match similar PA and non-PA pixels [20]. We must choose how many unprotected pixels to match to each protected pixel. As the number of matches rises, the variance of the impact estimate will fall, given more data. Yet, because not all protected pixels have many very similar unprotected pixels, increasing the number of matched unprotected pixels can lower the average matching similarity. We have used from one to four matches, sometimes using a 'calliper' to drop poor pixel matches.

If, as just noted, it is possible that the most similar matches are not always good, then although matching can greatly improve the similarity of the unprotected comparisons to protected pixels, it does not guarantee outstanding similarity. Thus, after matching, we must check for similarity, or balance, for each of the deforestation-and-protection-relevant characteristics used in matching. Given good matching, on average, we can estimate counterfactual deforestation for the PA (had it not been protected) and compare that with the actual deforestation of protected land.

Yet even with good matching, on average, there are always differences at the pixel level. To further reduce the influences of different characteristics between PAs and unprotected pixels, we can run a regression just like that in table 3 but adding a binary indicator for being protected. To be explicit, in order to preserve the gains in similarity from the matching, unlike table 3 this regression is run using only the protected pixels and the matched subset of all unprotected pixels. The

Table 2. Regressions for protected area siting choices using relevant characteristics. Standard errors in brackets. ***, $p < 0.01$.

	pre-2000 PAs		2000–2004 PAs	
probits	in the arc	not in arc	in the arc	not in arc
road distance 1985 (km)	0.3055***	0.1162***	0.3949***	0.1153***
	[0.004]	[0.003]	[0.004]	[0.003]
big city distance 1991 (km)	0.2294***	0.2547***	0.2812***	0.4940***
	[0.007]	[0.007]	[0.007]	[0.007]
forest edge distance 2000 (km)	0.1865***	−0.0807***	0.2284***	−0.0276***
	[0.002]	[0.002]	[0.002]	[0.002]
river distance (km)	−0.0032	0.1371***	−0.0196***	0.0822***
	[0.002]	[0.002]	[0.002]	[0.002]
soil fertility (1–5)	0.0528***	−0.0024	−0.0093***	0.0312***
	[0.003]	[0.002]	[0.004]	[0.003]
rainfall (mm)	−0.0008***	0.0003***	−0.0008***	0.0001***
	[0.000]	[0.000]	[0.000]	[0.000]
Cerrado (1/0)	0.1632***	−0.3346***	0.0748***	−0.1596***
	[0.012]	[0.032]	[0.012]	[0.033]
flatter slope (%)	−0.032***	−0.0085	0.0784***	−0.1683***
	[0.007]	[0.006]	[0.007]	[0.006]
Rondonia	1.2389***	—	0.8471***	—
	[0.020]		[0.025]	
Mato Grosso	−0.2053***	—	−0.4646***	—
	[0.020]		[0.025]	
Para	0.0111	—	0.3196***	—
	[0.019]		[0.024]	
Tocatins	0.1939***	—	−0.0448	—
	[0.040]		[0.044]	
Maranhao	omitted	—	omitted	—
Acre	—	−0.1331***	—	−0.5024***
		[0.019]		[0.017]
Amazonas	—	−0.5583***	—	−0.8435***
		[0.016]		[0.014]
Roraima	—	0.3025***	—	−0.0808***
		[0.018]		[0.016]
Amapa	—	omitted	—	omitted
constant	−6.7208***	−6.0394***	−7.8191***	−8.0445***
	[0.090]	[0.072]	[0.094]	[0.073]
# pixel observations	219 287	233 764	194 561	243 734

regression then further reduces bias from the remaining differences relevant to deforestation.

3. Results

As noted, table 1 shows that unprotected pixels' characteristics differ from those of PA pixels. Deforestation rates differ as well in table 1. Before matching, deforestation during 2000–2004, for instance, is around half of a per cent within the PAs but over 5% in unprotected areas. For 2004–2008, deforestation is almost 4% outside the PAs but again it is about half of a per cent in PAs established before 2000, and under a tenth of a per cent in PAs created after 2000.

Table 2 places facts from table 1 in Probit regressions for the binary protection indicator. Each pixel characteristic that could vary between PAs and unprotected pixels, e.g. road distance, is tested for whether it significantly influences the siting of PAs, controlling for all other factors. In short, for the two PA siting decisions—i.e. PA creation before 2000 and during 2000–2004—table 2 conveys that many deforestation-relevant characteristics influence the siting of PAs.

Table 3. Deforestation regressions for unprotected land using relevant characteristics. Standard errors in brackets. **, $p < 0.05$; ***, $p < 0.01$.

	deforestation 2000–2004		deforestation 2004–2008	
probits	in the arc	not in arc	in the arc	not in arc
road distance 1985 (km)	−0.1779***	−0.1511***	−0.0795***	−0.1923***
	[0.004]	[0.010]	[0.005]	[0.011]
big city distance 1991 (km)	−0.0948***	−0.2128***	0.0967***	−0.1309***
	[0.008]	[0.020]	[0.010]	[0.022]
forest edge distance 2000 (km)	−0.0803***	−0.3248***	−0.2132***	−0.2745***
	[0.003]	[0.010]	[0.004]	[0.010]
river distance (km)	0.0902***	0.0091	0.0857***	0.0615***
	[0.004]	[0.007]	[0.005]	[0.011]
soil fertility (1–5)	−0.0523***	−0.0010	0.0145**	0.0581***
	[0.005]	[0.011]	[0.006]	[0.013]
rainfall (mm)	0.0000	−0.0005***	−0.0003***	−0.0004***
	[0.000]	[0.000]	[0.000]	[0.000]
Cerrado (1/0)	−0.1775***	−0.3210***	−0.0639***	−0.2131**
	[0.018]	[0.079]	[0.019]	[0.087]
flatter slope (%)	0.0884***	0.0800***	0.0911***	0.1605***
	[0.010]	[0.028]	[0.012]	[0.032]
Rondonia	−1.3249***	—	0.1342***	—
	[0.023]		[0.034]	
Mato Grosso	−1.1463***	—	0.0511	—
	[0.020]		[0.032]	
Para	−1.3333	—	−0.1665	—
	[0.018]		[0.032]	
Tocatins	−1.4537	—	−0.1903	—
	[0.054]		[0.062]	
Maranhao	omitted	—	omitted	—
Acre	—	0.2467***	—	0.5131***
		[0.064]		[0.078]
Amazonas	—	−0.0320	—	0.3539***
		[0.055]		[0.070]
Roraima	—	−0.1484**	—	0.0471
		[0.070]		[0.086]
Amapa	—	omitted	—	omitted
constant	2.6829***	4.9395***	−0.6961***	2.7505***
	[0.114]	[0.213]	[0.140]	[0.239]
# pixel observations	161 987	166 795	130 808	148 639

Thus, one must ask whether the differences in deforestation in table 1 represent impacts of PAs on deforestation. It could be that, instead, those differences in deforestation are due to the difference in characteristics between protected and unprotected pixels (also seen within table 1). Table 3 shows that characteristics' differences could explain some differences in deforestation, because characteristics seen to be significant in siting (table 2) are significant for deforestation. That is consistent with matching in [7] for average PA impacts. However, because impacts can vary between PA types, given all the PA facts in table 1, we want to apply matching to PA types.

(a) Arc of deforestation, pre-2000, comparing types for 2000–2004 deforestation

Table 4's upper half (rows 1–6) gives impact estimates for the high-pressure 'arc of deforestation'. Recall that table 1 has much higher 2000–2004 and 2004–2008 deforestation in the arc than outside.

Table 4. Estimated 2000–2004 deforestation reductions owing to pre-2000 PAs. *, $p < 0.10$; ***, $p < 0.01$.

	(A) in the arc	(B) in the arc	(C) in the arc	(D) in the arc
PA type	indigenous	sustainable use	integral	integral minus sust. use
# treated pixels	41 186	10 925	5189	
(1) PAs' internal rates of deforestation	0.75%	2.49%	1.66%	
(2) deforestation rate for all unprotected pixels	10.39%	10.39%	10.39%	
(3) *simple differences in group means* unprotected deforestation rate minus that for PA forest pixels	9.64%***	7.90%***	8.73%***	0.83%*
(4) matched unprotected defor. rate: using four matches and calliper = 1%[a]	6.37%	7.39%	10.54%	
(5) simple differences in group means: now using the matched unprotected	5.62%	4.90%	8.88%	
(6) *propensity-score matching adjusted* again using matched unprotected but regression with matched data	5.30%***	4.47%***	8.33%***	3.86%***
	(A) not in arc	**(B) not in arc**	**(C) not in arc**	**(D) not in arc**
PA type	indigenous	sustainable use	integral	integral minus sust. use
# treated pixels	41 154	15 080	10 736	
(7) PAs' internal rates of deforestation	0.14%	0.15%	0.10%	
(8) all unprotected deforestation rate	0.80%	0.80%	0.80%	
(9) *simple differences in group means* unprotected deforestation rate minus that for PA forest pixels	0.66%***	0.64%***	0.69%***	0.05%
(10) matched unprotected defor. rate: using four matches and calliper = 1%[a]	0.68%	0.77%	0.93%	
(11) simple differences in group means: now using the matched unprotected	0.54%	0.61%	0.83%	
(12) *propensity-score matching adjusted* again using matched unprotected but regression with matched data	0.46%***	0.45%***	0.87%***	0.41%***

[a]There is impressively little difference between these estimates, fewer matches and even simple ordinary least squares (OLS).

Table 4's row 1 provides the observed internal rates of deforestation, within the PA types. Row 3's simplest possible impact estimates subtract row 1's deforestation in PAs from row 2's rate for all unprotected pixels (thus, positive numbers imply lower deforestation within the PAs). Without matching, all PA types are compared to the same unprotected deforestation rate (row 2). Thus, the differences in row 3 reflect the differences in internal deforestation across PA types. We can see, then, that internal deforestation is highest for the sustainable use PAs and is lowest for the Indigenous Lands, with the internal deforestation rates for the Integral PAs in the middle.

Internal deforestation is only one difference across types. PA siting, *vis-à-vis* pressure, also varied. We can tell by looking across table 4's row 4 for matched unprotected deforestation. This is the basis for row 6's impact estimates that compare this with deforestation in PAs (row 1). In row 6 column A, we see that the matching estimate of impact for Indigenous PAs is considerably lower, at just over half the magnitude, compared with row 3's impact estimate generated by simply subtracting the means. Thus, a significant fraction of the apparent PA impact in row 3 is owing to siting, i.e. differences in pixel characteristics between protected and unprotected—the differences addressed in matching. Column B conveys a similar result for sustainable use PAs. They are deforested more internally and, further, at least on average for states in the arc, their siting strategy involves some avoidance of deforestation pressure (row 4). Thus, their matching estimate of impact (row 6) is lower.

By contrast, siting bias towards low pressure does not seem to be present for Integral PAs. For column C, table 4's row 4 is essentially no different from row 2 for all unprotected land. Thus, impact estimates for Integral PAs from differences in group means (row 3) and matching (row 6) are very similar. In sum, the pre-2000 public PA strategies in the arc appear to support impacts from Integral PAs

Table 5. Estimated 2004–2008 deforestation reductions owing to pre-2000 PAs. *, $p < 0.10$; ***, $p < 0.01$.

	(A) in the arc	(B) in the arc	(C) in the arc	(D) in the arc
PA type	indigenous	sustainable use	integral	integral minus sust. use
# treated pixels	40 877	10 653	4915	
(1) PAs' internal rates of deforestation	0.16%	3.74%	1.18%	
(2) all unprotected deforestation rate	7.44%	7.44%	7.44%	
(3) *simple differences in group means* unprotected deforestation rate minus that for PA forest pixels	7.27%***	3.70%***	6.26%***	2.56%***
(4) matched unprotected defor. rate: using four matches and calliper = 1%[a]	6.04%	6.96%	6.62%	
(5) simple differences in group means: now using the matched unprotected	5.87%	3.22%	5.44%	
(6) *propensity-score matching adjusted* again using matched unprotected but regression with matched data	5.46%***	2.89%***	4.72%***	1.83%***
	(A) not in arc	**(B) not in arc**	**(C) not in arc**	**(D) not in arc**
PA type	indigenous	sustainable use	integral	integral minus sust. use
# treated pixels	40 668	15 049	10 402	
(7) PAs' internal rates of deforestation	0.03%	0.19%	0.03%	
(8) all unprotected deforestation rate	0.64%	0.64%	0.64%	
(9) *simple differences in group means* unprotected deforestation rate minus that for PA forest pixels	0.61%***	0.45%***	0.61%***	0.16%*
(10) matched unprotected defor. rate: using four matches and calliper = 1%[a]	0.58%	0.57%	0.71%	
(11) simple differences in group means: now using the matched unprotected	0.55%	0.38%	0.68%	
(12) *propensity-score matching adjusted* again using matched unprotected but regression with matched data	0.48%***	0.21%***	0.70%***	0.49%***

[a]There is impressively little difference between these estimates, fewer matches and even simple OLS.

relative to sustainable use by limiting internal deforestation and by siting, i.e. not avoiding pressure. Column D for the arc of deforestation conveys that the strategies' impacts add to a difference of almost 4%. In these high-pressure states, Integral PAs have greater impact. In light of that, we also highlight PAs' extents. Sustainable use PAs are almost twice the area.

The extent of Indigenous PAs requires its own explanation. Yet, we take the opportunity to show that public PA strategies need not all favour one PA type. Indigenous PAs, for example, have more siting bias than Sustainable Use PAs, yet less internal deforestation than Integral PAs.

(b) Regional variation in strategies and impacts (again pre-2000 protected areas, 2000–2004 deforestation)

Table 4's lower half (rows 7–12) examines the same questions for those states outside of the arc. Like row 1, row 7 provides observed internal rates of deforestation within each of the PA types. This region differs in that it lacks variation in internal deforestation rates across PA types. The values in row 7 of table 4 are essentially equal. That implies of course that the values in row 9 also will be equal, since row 9 subtracts row 7 from the constant row 8. This is confirmed by the lack of significance in column D for row 9 in table 4.

Differences across PA types in siting strategies still might induce differences in impacts. Table 4's row 10 suggests that, during this initial period of PA creation that we observe, perhaps the PA strategies outside of the arc of deforestation are akin to the strategies pursued in the arc: row 10's matched unprotected deforestation, in comparison with row 8, suggests a fall in impact owing to siting for Indigenous and sustainable use—just as in the arc[8]—but a rise for Integral PAs. Column D for row 12's matching estimates of impact suggests that this helps to create a tiny difference.

However, stepping back, given the low level of pressure the impacts in row 12 are all very small. Thus, while we are glad to document with precision the estimates generated by our sample,

Table 6. Estimated 2004–2008 deforestation reductions owing to 2000–2004 PAs. ***, $p < 0.01$.

	(A) in the arc	(B) in the arc	(C) in the arc	(D) in the arc
PA type	indigenous	sustainable use	integral	integral minus sust. use
# treated pixels	5957	594	755	
(1) PAs' internal rates of deforestation	0.24%	0.00%	0.26%	
(2) all unprotected deforestation rate	7.44%	7.44%	7.44%	
(3) *simple differences in group means* unprotected deforestation rate minus that for PA forest pixels	7.20%***	7.44%***	7.17%***	−0.26%
(4) matched unprotected defor. rate: using four matches and calliper = 1%	4.54%	7.14%	8.61%	
(5) simple differences in group means: now using the matched unprotected	4.30%	7.14%	8.34%	
(6) *propensity-score matching adjusted* again using matched unprotected but regression with matched data	4.63%***	6.99%***	9.51%***	2.52%***
	(A) not in arc	**(B) not in arc**	**(C) not in arc**	**(D) not in arc**
PA type	indigenous	sustainable use	integral	integral minus sust. use
# treated pixels	15 264	9505	4207	
(7) PAs' internal rates of deforestation	0.02%	0.07%	0.00%	
(8) all unprotected deforestation rate	0.64%	0.64%	0.64%	
(9) *simple differences in group means* unprotected deforestation rate minus that for PA forest pixels	0.62%***	0.57%***	0.64%***	0.07%
(10) matched unprotected defor. rate: using four matches and calliper = 1%	0.24%	0.28%	0.46%	
(11) simple differences in group means: now using the matched unprotected	0.22%	0.21%	0.46%	
(12) *propensity-score matching adjusted* again using matched unprotected but regression with matched data	0.19%***	0.23%***	−0.05%	−0.28%

effectively all of these impact estimates are very close to the same. Thus, the relative impact of Integral versus Sustainable clearly differs outside the arc versus in it. Also, once again, we highlight the variation in extent across types in light of the relative impacts: for these states compared to the arc, Indigenous extent is about the same but Integral's is about double.

(c) Temporal variation within impact by protected area type (pre-2000 protected areas, 2004–2008 deforestation)

Table 5—same PAs but later deforestation—makes the simple but critical point that time itself shifts PA impacts. Put another way: if pressures shift, even the best-laid PA plans could go awry. That echoes the findings reported in [21], which considers Panama, where the same PAs shift in impacts across periods—with a policy implication that anticipating shifts in deforestation pressures could improve planning for impacts.[9]

We want to see how deforestation pressure shifts affect relative impacts across PA types. Table 5's row 1 shows even more difference in internal deforestation—relative to table 4's row 1—between Integral PAs and sustainable use. Thus for the same fixed PA locations used in table 4, there is an effective shift in strategy on internal deforestation, even if public actions did not shift—though, as noted above, public choices may respond to pressures, including for deforestation.

Further, the differences in siting by type have different implications for this time period: in table 4, Integral PAs are not biased in siting away from the 2000–2004 deforestation pressure (focusing here on the arc of deforestation, where higher pressure actually permits PA impacts); yet during 2004–2008 (table 5), the same fixed PA sites are away from deforestation pressure (column C, row 4 versus row 2). By contrast, looking at indigenous PAs, comparing table 5's row 4-versus-row 2 difference with table 4's column A would suggest that the deforestation pressures have moved towards the Indigenous PAs.

(d) A new regime? Again comparing protected area types (2000–2004 protected areas, 2004–2008 deforestation)

Table 6's upper half (rows 1–6, plus extent indicated by '# treated pixels') illustrates significant shifts in PA strategy for the arc of deforestation (given little PA impact outside the arc and no differences by type there, we focus on the arc). Immediately standing out are the extent strategies: there are almost zero non-indigenous areas. That is not the case outside of the arc and, once again, we highlight a possible correlation with impacts, as PA impacts outside of the arc are much lower.

Table 6's row 1 shows another strategy difference for new PAs: in internal deforestation. Unlike row 1 in either table 4 or table 5 (pre-2000 PAs, in arc, either period of deforestation), table 6 for 2000–2004 PAs shows no difference across types in internal deforestation (row 1) or, as a direct consequence, the impact estimates generated by simple means differences (row 3, column D confirms no statistical difference across types). That is a change from pre-2000 PAs.

Finally, a third shift in PA strategy is in the siting of these 2000–2004 PAs, as can be seen in table 6 row 4. While column A has ongoing bias towards low pressure for Indigenous lands, in column B for the sustainable use PAs row 4—and thus row 6's matching impact estimates—suggests much less bias away from pressure for new PAs. That raises the impacts of those new PAs.

The little Integral area created in the arc also shows different siting for 2000–2004 PAs. Column C's row 4 (versus row 2) shows Integral siting biased *near to* pressure, for whatever reason (maybe public actors targeted impact, or simply were running short of lands for PAs in the arc), confirmed by a matching estimate of deforestation impact (row 6) above the simpler one (row 3). For matching impact estimates (row 6), column D confirms Integral above sustainable use.

This is a fitting final point. It repeats table 4's net result for the arc, while confirming that shifts in strategy can alter impact rankings. The prior arc result, unlike this, relied upon internal deforestation. This arc result relies on siting near pressure, instead of away from it. Table 6 also confirms drastically different impact outside the arc versus in it—for each type and across types.

4. Discussion

We estimated the deforestation impacts of PA types for a critical frontier, the Brazilian Amazon. We separated regions and time periods that differ in their deforestation and political pressures and documented considerable variation in PA strategies across regions, time periods and types. The siting of PAs varies across regions. For example, all else being equal, PAs in the arc of deforestation are relatively far from non-forest, while in other states they are relatively near. Internal deforestation rates vary across time periods, e.g. they are more similar across PA types for PAs after 2000. By contrast, after 2000, PA extent is less similar across PA types, with little non-indigenous area created inside the arc. PA strategies generate a range of impacts for PA types—always far higher within the arc—but not a consistent ranking of PA types by impact.

In sum, we documented variation in how much each type is used (extent), where (siting), and how much internal deforestation occurs—and each of those elements affects total impacts. For example, they may combine differently even if we observe a consistent impact per hectare. For pre-2000 PAs in the arc, impacts of Integral PAs are greater than impacts of sustainable use PAs because the latter have more internal deforestation and more siting bias away from pressure. For post-2000 PAs in the arc, though, the reason why Integral PAs have more impact is that they are sited near pressure. None of those stories—nor any significant PA impact—arose outside the arc.

These results for a single country, indeed just one enormous region of one single country, should help to put to rest any expectations that one type of PA will always achieve more impact. There are global tendencies [4,8] but our results support closer study of any particular context, because there are so many 'moving parts' that differ across contexts and will influence impacts. Within the Amazon, the impacts for a single state can be distinct from its wider region (e.g. [9]).

This consideration of multiple key elements suggests varied possibilities for PA strategies to respond productively according to context. For example, as Albers [27] suggests, sometimes it will be critical to understand how enforcement occurs, and sometimes PA inhabitants accomplish it best. Likewise, sometimes it will be critical to know how the location of a PA will interact with local development, such as migration or the public construction of new roads (e.g. [24–26]).

Finally, we should highlight that objectives are implicit in all this discussion of strategies. Here, we used the word 'public' to indicate a great range of actors making a range of decisions. However, it is clear that the varied actors relevant for these decisions differ in their objectives. That could add yet another layer into our understanding of how PAs can have impact.

Data accessibility. The forest data can be downloaded from INPE, PAs from IBGE. The data for all the characteristics of forest locations that are relevant for deforestation also are available.

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Endnotes

[1]See, for example, [1] for average PA impacts in Costa Rica and [2] for variations in PA impact for subsets based on values of deforestation pressure drivers. Also, Joppa & Pfaff [3,4] find that patterns seen in Costa Rica also are rather prevalent globally, though we stress that their findings from over 100 countries include figures showing the variations across countries.

[2]The paper notes that matching may be useful in controlling for land and site characteristics but does not employ it. Using matching to try to hold all else observationally equal, Nolte *et al*. [6] note lower internal deforestation within strict PAs. Per enforcement, we also measure internal clearing and show that such differences actually can vary considerably.

[3]We also apply the 'East' versus 'West' division of Amazon states used in [7]. This bolsters our core conclusions about variations in public PA strategies and wide variation within, yet no fixed ranking among, impacts by PA type. Note that additional PAs were

established after 2004. We would expect further variations in strategies and impacts.

[4]A prior review [11] notes hurdles for common approaches. See also [12–16], which review past evaluations.

[5]For categorising the many types of protection that have been created around the world, IUCN provides a globally applicable strictness ranking by translating local terms into comparable categories, from highest (I) to lowest (VI).

[6]The site http://www.planalto.gov.br/ccivil_03/Leis/L9985.htm shows the law that creates a national system of PAs. It defines types in Chapter III. Sustainable forest management is regulated by the forest code, as well as by decree.

[7]These are very widely used data (see, for example, use in [18]) but we cannot claim they are perfect. We do not have reason to believe that any particular local issues (in space or time) should affect our conclusions.

[8]For the arc, Rosenbaum bounds suggest that large hidden biases would be required to explain PAs' significance.

[9]One might naturally, then, next ask about spatially guiding how deforestation pressure unfolds on the landscape. Spatially guiding development is precisely the focus of Pfaff *et al*. [22,23], concerning implications of a spatial intensification of roads, while Herrera [24–26] considers PAs' spillovers to development decisions, including migration and road building.

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