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Deforestation trends and impact assessment of protected area designation in the South-American Tri-national Atlantic Forest

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Abstract

The South-American Atlantic Forest region spans the nations of Argentina, Brazil and Paraguay. It is one of the most ecologically diverse in the world, yet one of the most vulnerable to deforestation with little research examining trends and drivers. Conservation interventions can play a critical role in protecting this forest, but the impact of their implementation remains unclear. We assessed the effects of forest protected area (FPA) designation on avoided deforestation across the Atlantic Forest region between 2000 and 2020 using the most recently available remote-sensed data in combination with geo-referenced socio-economic descriptors. Applying a pseudo-randomized approach, we quantified factors explaining establishment of FPAs and compared deforestation rates. Results show FPA designation lowered the odds of deforestation by about 14%, which is significantly higher than past assessments in other Latin American regions. Effectively, the estimated deforestation rate within FPA-designated areas (~5%) was nearly four-times lower than in non-FPA forests (19%). Future studies are needed to assess the impacts of FPAs on the socioeconomic wellbeing of forest-dependent communities across the Atlantic forest.

Keywords: Deforestation and forest degradation, Financial mechanisms, Monitoring and data collection, Research, Governance

Introduction, scope and main objectives

South America's Atlantic Forest region is a hotspot of global biological diversity hosting about 7% of the world's plant species (Willis 2017), 5% of its vertebrate species (IUCN 2021), and a reported tree richness of up to 443 species per hectare (Di Bitteti et al. 2003). The region's biological diversity and richness have increasingly become in danger from deforestation and forest degradation pressures. The region has reportedly lost about 27,000 km^2 of natural vegetation between 2000 and 2019 (MapBiomas 2021), thus, attracting global attention and highlighting the need to determine whether conservation interventions can reduce land conversion pressures (Myers et al. 2000; Olson and Dinerstein 2002; Di Bitetti et al. 2003; WWF 2015).

The establishment of Forest Protected Areas (FPAs) has become a major conservation intervention in the region. FPAs, despite their prolific establishment, have not been robustly assessed for the degree to which they can yield ecological and social benefits in the region. Here, we report an evaluation of the impact of FPAs across South America's Atlantic Forest region in preventing deforestation between the years 2000 and 2020. Our analysis is premised on how the probability of land use change, from forests to non-forest uses, is driven by land rent factors. Forestland's opportunity costs of alternative uses can create an incentive for conversion when expected rents exceed net present value for the conservation of forests (Zhang and Pearse 2011). Designation of forests within an FPA for strict conservation partly aims to reduce land opportunity costs by outright preventing, or at least reducing, any potential rents from other uses (Angelsen 2010).

We focus our analysis on FPAs established in a region inclusive of Alto Paraná (Brazil), Misiones (Argentina), and Paraná (Paraguay) prior to the year 2000. Each FPA was categorized as one of seven different types as defined by the International Union for the Conservation of Nature-IUCN (Dudley 2008) namely: Strict Nature Reserve, Wilderness Area, National Park, Natural Monument or Feature, Habitat/Species Management Area, Protected Landscape, Protected area with Sustainable Use of Natural Resources.

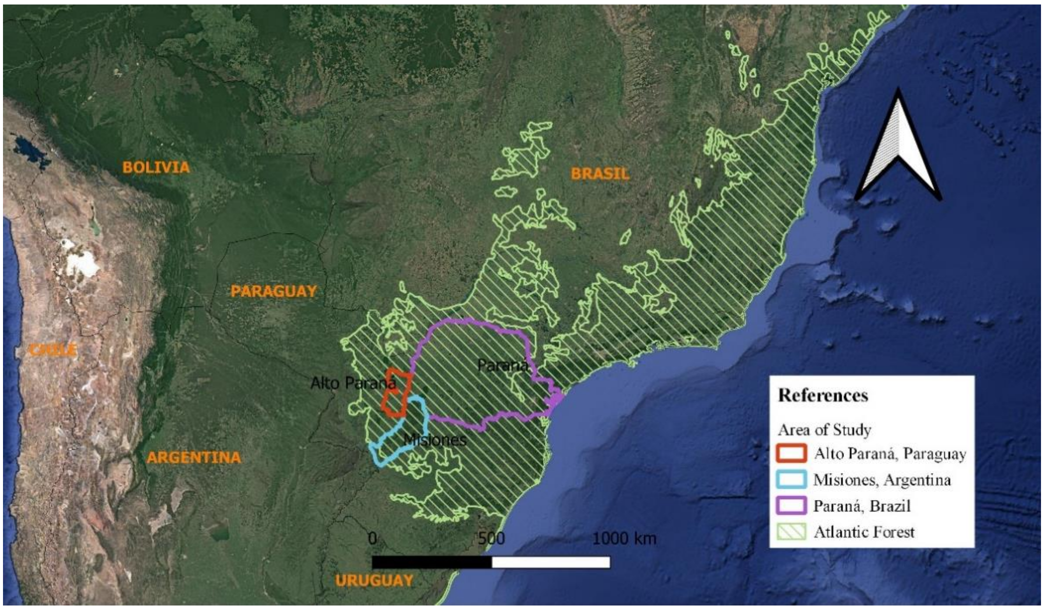
Our specific objectives are to:

- Determine land rent factors systematically explaining the location of FPA establishment
- Assess the net impact of FPA establishment in reducing deforestation
- Discuss prospective conditions that could enhance the effectiveness of FPAs in reducing deforestation in South America’s Atlantic Forest region

Our work assessing the role of conservation interventions in avoiding deforestation is directly relevant to Sustainable Development Goals “Climate Action”, and “Life on Land”

Methodology

Our unit of observation is a 25-by-25-meter pixel for which forest cover was modeled from Landsat TM imagery between the years 2000 and 2020 within the boundaries of the ecoregions encompassing Alto Paraná Atlantic Forest, Araucaria Moist Forests, and Serra Do Mar Coastal Forests (Bailey 2014). We restricted our sample to only pixels with forest cover as of the year 2000 determined by a canopy density criterion ≥ 30%, which is the most frequently adopted standard for forest designation using satellite imagery (World Resources Institute 2021). We show the area studied in Figure 1 highlighting the tri-national park.



Source: Google Maps (2021)

Fig. 1: Paraná Forest ecoregion highlighting study area within South America´s Atlantic Forest.

Our systematic analysis of FPAs effect on lowering deforestation was completed in two steps. First, we pseudo-randomized the overall sample by matching one-to-one pixels that were in, and under no FPA categorization, based on land rent variables. This step helped reduce the non-random nature of FPA establishment. We followed a propensity score matching (PSM) technique in R using the "Matchit" package. We matched one-to-one pixels in our georeferenced dataset from both groups (FPA, non-FPA) based on estimated probability scores from a logit model and specified a one-to-one nearest neighbor comparison with replacement based on a 0.5 caliper distance. Second, after PSM, we assessed mean differences for the likelihood of deforestation associated with FPA designation. The probability of FPA designation for a pixel in our sample was given by:

$$\text{Prob (FPA)/ Prob (Non-FPA)} = \text{prob}(x)/ (1-\text{prob}(x)),$$

denoting the odds of a pixel being under FPA designation in 2000. We studied these odds as a logistic (log) function of a vector x of explanatory factors underlying a pixel's land rent:

$$\log \text{prob}(x) /(1-\text{prob}(x)) = x\beta+\varepsilon,$$

capturing linear β associations with a vector of explanatory variables of the log-odds of deforestation with a random noise (ε) following a logistic distribution (Caliendo and Kopeinig 2008). Differences in means, post PSM, were compared for statistical significance.

Table 1 outlines IUCN categories for FPAs found in the region. Across our sample, most FPA pixels were found in the National Park category. In Alto Paraná, the majority of FPAs were Habitat Species Management Areas, followed by Wilderness Areas, Strict Nature reserves, and Protected Landscapes. In Misiones, the greatest portion of FPAs were Protected Area with Sustainable Use of Natural Resources, followed by National Parks. In Paraná the greatest portion of FPAs were National Parks, followed by Protected Landscapes and Strict Nature Reserves.

Table 1: IUCN categories of forest protected areas found in South America's Upper Paraná Atlantic Forest region

Province	Ia	Ib	II	III	IV	V	VI	Not Applicable/Not Reported
Alto Paraná	11.76%	0.00%	11.76%	0.00%	70.59%	5.88%	0.00%	0.00%
Misiones	6.12%	2.04%	38.78%	2.04%	0.00%	2.04%	42.86%	6.12%
Paraná	10.00%	1.25%	28.75%	2.50%	6.25%	15.00%	5.00%	31.25%
Total	8.90%	1.37%	30.14%	2.05%	11.64%	9.59%	17.12%	19.18%

We assembled a geospatial database in QGIS as outlined in Table 2 including sources of remotely-sensed information on forest conditions and secondary data at municipal and national levels for socio-economic information. These were the more spatially-explicit and current data sources available to us at the time of the study. We first identified the presence of FPAs by including a layer from the World Database on Protected Areas (IUCN n.d.). Since we focused on evaluating the impact of FPAs established by 2000, this layer was based on only those established prior to 2000 as our baseline for forest cover. We then compiled forest composition and subsequent loss from maps developed by Global Forests Watch (Hansen et al. 2013). These data depict forest loss within 25-by-25-meter pixels modeled from Landsat TM imagery between the years 2000 and 2020.

Table 2: Variables included in the analysis of deforestation

Data	Description	Original data format and scale	Source
Forest cover	Identification of forest cover: 1=Forested; 0=Land change	Pixel (25 25 m)	Hansen et al. (2013)
Elevation	Continuous variable (m): Meters above sea level	M.a.s.l., raster	USGS EROS Center (2018)
Political boundaries	Country- and provincial-level boundaries: Categorical variables with baseline level	National/provincial polygon shapefiles	Conservation Biology Institute (2021)
Roads	Euclidean distance to nearest road (Km)	Line shapefile	OpenStreetMap (2021)
Ports	Euclidean distance to nearest port (Km)	Point shapefile	Google Earth Imagery (2021)
Designated FPA	Legally-recognized conservation areas; 1= FPA designation; 0= Otherwise	Polygon shapefile	UNEP-WCMC (2019)
Population density	Time-variant (Change in inhabitants/ km^2)	Pixel (30 degree arc seconds)	CIESIN (2018)
Net Primary Productivity (NPP)	Estimate of land productivity if used for agricultural purposes	Pixel (30 degree arc seconds)	Imhoff et al. (2004)

Results

Table 3 shows results of the logistic regression used to calculate propensity scores and quantify socioeconomic and land use value covariates explaining the likelihood of FPA. All the models' independent variables were found to be statistically significant, except for the variable linear distance to nearest roads (km). Odds ratios (ORs) indicate an inverse relationship between elevation and the odds of a forest being designated as a FPA. For instance, on average the odds of FPA designation were 26% lower with every 100-meter increase in elevation. The estimated effects of proximity to roads, ports and cities were found to have a more complex relationship with FPA designation. While linear distance to nearest road was found to be statistically insignificant, quadratic distance was found significant and to have a positive relationship with FPA designation. Coefficients suggest that the odds of FPA designation were lower with longer distances from the nearest road. FPA distance to nearest city or port show statistically significant linear and quadratic effects. Results indicate that for every 1-km greater linear distance to cities and ports, forests were 1% and 2% less likely to have an FPA designation. With 1-km square greater quadratic distance to cities and ports, forests were found to have had near equal changes of having an FPA designation. Net Primary Productivity (NPP) was found to be statistically significant and to have an inverse relationship with FPA designation. For every 1,000 metric tons increase in NPP, a forest was 1% less likely to be designated an FPA. The percent change in population density between 2000 and 2020 was also found to be significant. A 1% increase in population density during this period was associated with a 0.7% increase in the likelihood of a forest having an FPA designation.

Table 3: Coefficients, odds-ratios and p-values for the probability of FPA denomination using logistic regression

Attributes	coef.	OR	*p*-value
(Intercept)	1.836	6.271	<0.001
Elevation (100 m)	-0.176	0.839	<0.001
Distance to nearest road (Km)	-0.001	0.999	0.570
Distance to nearest road -squared (Km^2)	0.001	1.001	<0.001
Distance to nearest city (Km)	-0.015	0.985	<0.001
Distance to nearest city -squared (Km^2)	0.000	1.000	<0.001
Distance to nearest port (Km)	-0.005	0.995	<0.001
Distance to nearest port-squared (Km^2)	0.000	1.000	<0.001
NPP (1,000 metric tons)	-0.001	0.999	<0.001
Population Density Change (Percent)	0.007	1.007	<0.001

Results of FPA designation show it had an average effect on avoiding deforestation of 14.16% (Table 4). This was estimated post-PSM from a dataset of 27,216 pixels, with 17,689 in FPAs and 9,527 outside FPAs. Differences in proportions of deforested pixels were statistically-significant (*p*-value <0.01). Estimated deforestation within FPA-designated areas was 4.88%, as compared with 19.04% in non-FPA forests. This is about four-times a lower deforestation rate within protected forests.

Table 4: Estimated average effect of FPA designation in avoiding deforestation

	Non-FPA		FPA			Average effect of PFA (%)
	n	%	n	%	*p*	
All	94,333	18.16	17,692	4.15	<0.01	
PSM-matched	9,527	19.04	17,689	4.88	<0.01	14.16

Discussion

We found FPA to be less likely located in forests with greater NPP but more likely in areas that experienced increased population density between 2000 and 2020. This finding may support Mather and Needle (1998) forest transition theory that predicts that industrialization and urbanization lead to the abandonment of marginal lands and the eventual recovery of natural systems. Although our estimates indicate FPAs have experienced an increase in total population densities, this trend may reverse due to a predicted loss of nearly a third of the region's rural population to urban areas by the year 2050 (FAOSTAT 2021). Despite these pending socio-economic changes, the environmental, economic, and political context of the region as well as direct drivers of deforestation such as soil conditions and government subsidies, in perennial crops, cattle production, and plantations of exotic species and other traditional agricultural practices may continue to cause elevated forest loss.

We found FPAs in the region to have an average effect of 14.16% across designated areas. This finding is higher than those of other impact evaluations across Latin America. In a study of 10 FPA programs across Peru between 2000 and 2006, Miranda et al. (2014) found the impact of FPA to be less than 1 percent in preventing forest cover loss. Geldmann et al. (2013) performed a metanalysis of FPAs across Latin America and found 86% of studies to have found evidence that FPAs prevent deforestation and wildlife population declines. Higher estimated impacts than other FPAs in across Latin America might be due to the elevated rate of deforestation outside of Atlantic Forest FPAs and the longer duration of our study, which has not always been possible due to limitations in remote sensing data.

Advanced understanding of FPA impact on deforestation is critical, but conservation efforts could be greatly improved if complemented with on-the-field research and practice. To fully know if FPAs are sustainable and providing sustainable development solutions, more time is needed to measure socio-economic conditions of forest-dependent communities surrounding FPAs. In addition, focusing on deforestation via satellite imagery, misses the impacts FPAs may have in preventing forest degradation and wildlife biodiversity, which will require field level assessment (Mohebalian and Aguilar 2018). Lastly, deforestation does not occur in a vacuum and longer-term impact assessment could include dynamic socio-economic conditions that impact expected land rents and institutions preventing the destruction of local ecosystems.

Conclusions

Land rent factors systematically determined the location of FPA establishment across the Atlantic Forest region of South America. FPA were found less likely to be established with increased distance roads, cities, and ports. FPA were also found to be less likely in higher elevation and while they were less likely to have forests of higher NPP values they were more likely to have experienced an increase in their population density between 2000 and 2020. These factors seem to point to FPAs established prior to 2000 having lower alternative land use values than non-FPA forests.

Our finding that FPAs provided 14.16% additional forests cover protection compared to non-FPA forests indicates the FPAs in the region had positive ecological impacts. A factor which may have influenced this outcome could lie in the land rent biases we measured in the placement of FPAs in the regions. Future placement of FPAs in locations of greater alternative economic value may enhance the probability of similar forests not being cleared for alternative uses.

Although we found evidence to support the ecological impacts of FPAs in the region the long-term sustainability of these FPAs will rely on the socioeconomic conditions of the people living in surrounding communities. We are yet to understand the impact of FPAs on human well-being such as income and food security. Further efforts can be placed on supporting good governance and participation in forest resource management as well as social safety net programs aimed at poverty alleviation. Further study of prevented degradation, beyond outright deforestation, seems warranted for this ecological region of global importance.

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