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Deforestation in South America's tri-national Paraná Atlantic Forest: Trends and associational factors

Phillip M. Mohebalian [a], Lucas N. Lopez [b], Angela Bárbara Tischner [c], Francisco X. Aguilar [d,*]

[a] US Census Bureau, USA
[b] School of Forestry, National University of Misiones, Argentina
[c] Itaipu Technological Park Foundation, Brazil
[d] Department of Forest Economics, Swedish University of Agricultural Sciences, Sweden

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ABSTRACT

South America's Tri-national Paraná Atlantic Forest, an ecological region spanning across the nations of Argentina, Brazil and Paraguay, is one of the most diverse in the world but also one of the most vulnerable to deforestation. A review of public policy interventions shows all three governments have taken major legislative steps to protect remaining forests, but studies evaluating deforestation trends and associated factors in this region are scarce or non-existent. Here, we make a direct contribution to this knowledge gap by assessing deforestation trends within Paraná Atlantic forests of Argentina's Misiones, Brazil's Paraná, and Paraguay's Alto Paraná between 2000 and 2020. Over this period about 20% of forest cover was lost in Misiones, 13% in Paraná, and 18% in Alto Paraná. The odds of observed deforestation, else constant, showed nuanced associations with proximity to nearest roads, cities, and ports. Higher levels of economic growth were directly associated with deforestation, as were increases in population density over the entire period. Protected area designation between years 2000 and 2020 showed effectiveness in lowering odds of deforestation with heterogeneous associations across countries. Our results reflect associational inferences with estimated deforestation; future research should investigate causal effects of protected designation, and assess its role in avoided degradation and wider socio-economic impacts.

1. Introduction

South America's Tri-national Paraná Atlantic Forest region is a hotspot of global biological diversity that has become increasingly vulnerable to deforestation and forest degradation pressures in recent decades. The region spanned over an estimated 1,345,300 km^2 with 92% of its forest cover located in Brazil, 6% in Paraguay, and 2% in Argentina in pre-Columbian times (FVSA and WWF, 2017). Ecologically, Paraná Atlantic Forests can be divided into 15 terrestrial ecoregions ranging from montane savanna and mangroves to dry and moist forests encompassing tropical and subtropical areas (Olson and Dinerstein, 2002; Di Bitetti et al., 2003). Its altitudinal gradient extends from sea-level forests to mountain forests and grasslands above 2700 m above sea level (m.a.s.l.). Paraná Atlantic Forests are endowed with distinctive flora and fauna with a high degree of species richness, rare habitats, unusually high taxa, and endemic tree species such as Paraná pine (*Araucaria angustifolia*), yerba mate (*Ilex paraguariensis*) and bird species such as the Saw-billed Hermit (*Ramphodon naevius*), among many others (Goerck, 1999; Olson and Dinerstein, 2002; Di Bitetti et al., 2003; FVSA and WWF, 2017). While accounting for about 3% of global forestland, ecoregions of the Paraná Atlantic Forest are home to an estimated 7% of the world's plant species (Willis, 2017), and 5% of vertebrate species including reptiles, amphibians, fish, and birds (IUCN, 2021). There are an estimated 687 bird species identified in the region (Goerck, 1999) and some areas have a recorded tree diversity richness of up to 443 species per hectare (Di Bitetti et al., 2003). Comparatively, global tropical forests have a tree species richness on average of 154 species per hectare (Latham and Ricklefs, 1993) and bird species diversity per hectare range from 122 to 782 in South American forests (WWF, 2006a).

The Paraná Atlantic Forest is vulnerable to deforestation and habitat degradation. Its forested landscapes have become highly fragmented, which coupled with habitat loss, poses a major threat to local biodiversity particularly for large mammals. For instance, the most recent estimated population of the jaguar (*Panthera onca*), the largest carnivore

* Corresponding author.
E-mail address: Francisco.aguilar@slu.se (F.X. Aguilar).

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and top predator in the region, was of 300 individuals in 2020 which is about 1% of the estimated population at the dawn of the Anthropocene. Jaguars are currently found in less than 4% of the region, in 13 fragmented landscapes (Di Bitetti et al., 2003; FVSA, 2020). Biodiversity losses can be linked to anthropogenic factors with the most recent human population density in the region reaching 110 inhabitants per km^2 (about 148 million individuals in 2017), almost 25 times the current density across South America's Amazon rainforest. Across the entire region a net loss in all natural vegetation of 27,000 km^2 occurred between the 2000–2019 period (MapBiomas, 2019). The combination of ecological diversity and a trend of habitat loss has attracted global attention to this critically endangered region (Myers et al., 2000; Olson and Dinerstein, 2002; Di Bitetti et al., 2003; WWF, 2015).

Here, we respond to an extant gap in the fundamental assessment of deforestation trends within the Paraná Atlantic Forest's ecoregion by evaluating recent losses in forest cover and quantifying associated biological and socio-economic factors. Empirically, we focus our assessment on the Paraná Atlantic Forests extending across the province of Misiones in Argentina, the department of Alto Paraná in Paraguay, and the state of Paraná in Brazil (Fig. 1). Our specific objectives are to: (1) document a brief history of forest conservation strategies in the region emphasizing landmark legislation, (2) quantify deforestation trends since the turn of the 21st century using the best-available information, (3) assess leading factors associated with greater likelihood of deforestation, and (4) evaluate whether the designation of forestland under strict conservation showed lower deforestation odds. We emphasize that, challenged by information available, our study cannot make causal inferences about the impact of protected designation in preventing deforestation and findings are limited to associational inferences.

Our paper is structured as follows: Section 2 provides a timeline of landmark legislation supporting conservation in South America's Paraná Atlantic Forest region; Section 3 outlines research methods including data and econometric analyses; Section 4 provides descriptive statistics of deforestation in the region and the results of modelling factors associated with odds of deforestation; Section 5 summarizes our findings and offers conclusions.

2. Public efforts to conserve South America's Paraná Atlantic forests

Argentina has some 479,000 km^2 remaining of native forests accounting for 17.5% of its continental national territory (MAyDS, 2020b). Native forests are divided in seven forest regions according to climatic conditions, vegetation structure, and composition. The Atlantic Forest (also known in Argentina as 'Selva Misionera' or 'Selva Paranaense') is one of the nation's seven native forest regions located in the northeastern border with Brazil and Paraguay, enclosed within the province of Misiones.

Argentina started implementing various legal tools to promote the management, conservation, and restoration of native forests as early as 1898. Table 1 outlines landmark legislation that targets forest conservation in the country. For instance, The National Law 26331 "Minimum budgets for environmental protection of native forests" implemented in 2007 earmarks no less than 0.3% of the annual national budget, plus 2%

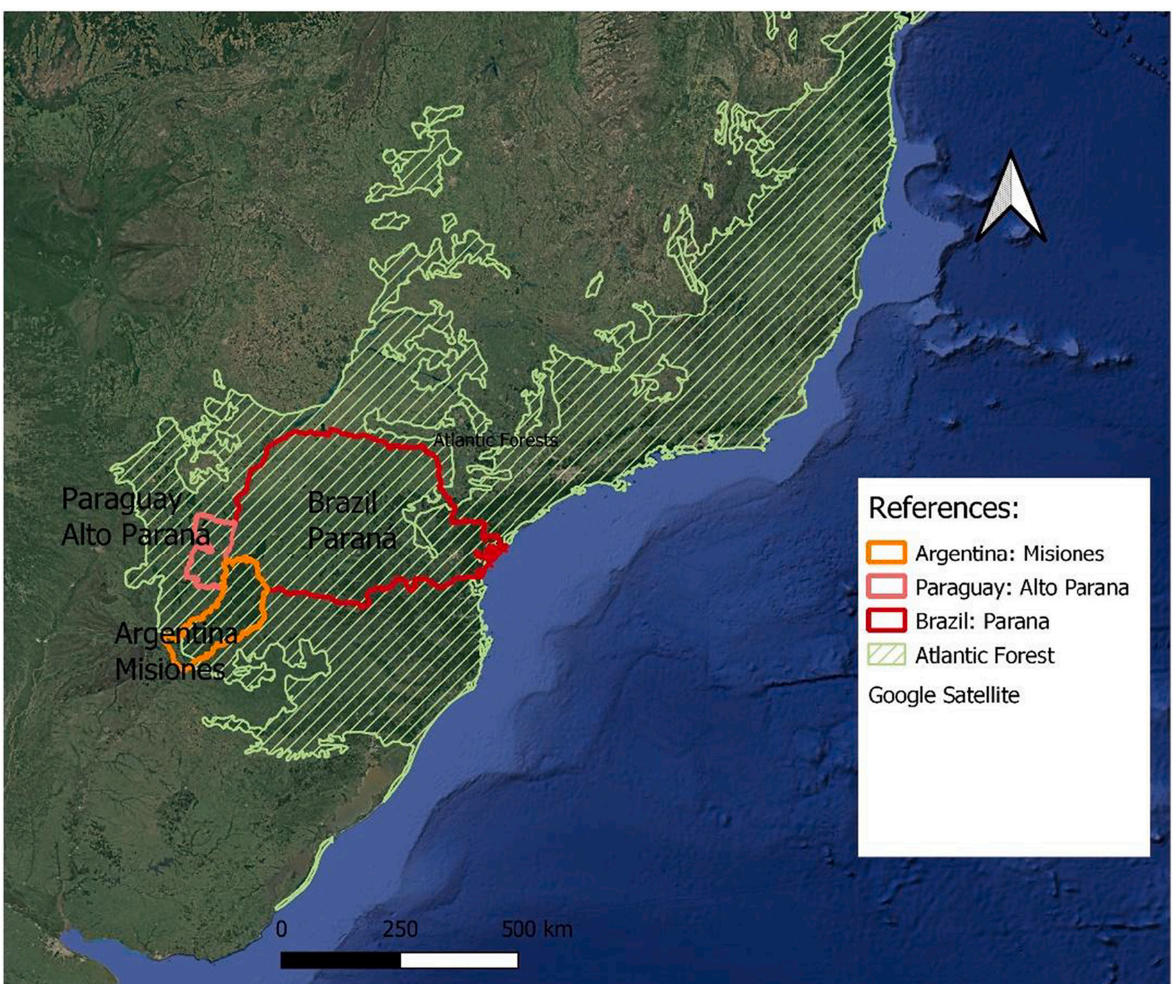

Fig. 1. Paraná Atlantic Forest ecoregion (dashed area), highlighting region of study within the Paraná Atlantic Forest. Source: Google Earth Imagery (2021).

Table 1
Landmark Argentinean legislation addressing native forest conservation, restoration of degraded areas and promotion of sustainable forest uses.

Enactment year	Number	Name	Citation	Brief description
1898	3727	National Public Administration Ministries of the Executive Power - its organization	National Public Administration (1898)	Organization of the ministries of the executive power, where established the regime and management of national forests department and its promotion in the 23 provinces.
1902	4167	Sale of public lands - adjudication of lands - creation of towns	Public Lands (1902)	Regime for Land adjudication and towns' creation. Among others, it provided regulations for the use of forest.
1948	13273	Defense of Forest Wealth	Forest wealth (1984)	Defense, improvement, and expansion of forests. Declared of public interest the defense, improvement, and expansion of the forests
1977	21695	Fiscal incentives for afforestation	Afforestation (1977)	Fiscal incentives for afforestation. Implemented a tax credit mechanism for afforestation programs.
1980	22211	Investments in low productivity rural lands	Low productivity land (1980)	Promotion for increasing agricultural production in low-productivity rural lands.
1997	24857	Fiscal stability for native forests	Fiscal stability (1997)	Fiscal stability for use of forests.
1999	25080	Investments for cultivated forests" Law 25,509 "Real right of forest area	Forest investments (1999)	Promotion of land use change for agriculture activities in areas covered by native forest categorized as low productivity areas.
2007	26331	Minimum Budgets for environmental protection of native forests	Minimum Budgets (2007)	Establish the minimum environmental protection budgets for the enrichment, restoration, conservation, use and sustainable management of native forests.

withholdings (gross income earned) of all exports of primary and secondary products from agriculture, livestock, and forestry, to the protection of native forests. Other sources of financing and public donations strengthen this legal tool including the Green Climate Fund (2020) which played an important role in supporting Argentina's REDD+ strategy. Despite these efforts, an estimated 43% of forest cover (some 65,000 km^2) was lost between 1998 and 2018. Loss of native forests have been attributed to agricultural expansion (e.g., growing of oilseed and cereals), and livestock (MAyDS, 2020a).

In Argentina, the Paraná Atlantic Forest extends solely across the province of Misiones with a total area of forest exceeding 15,000 km^2 (MADS, 2020b). Besides national conservation policies, the province of Misiones implemented the provincial Law XVI N° 60 Green Corridor (Spanish: "Corredor Verde") in 1999. This law placed normative constraints restricting land use change on about 37% (11,026 km^2) of the total land area and created a fund for sustainable management of the forests. The area set aside for conservation now hosts 63 protected areas with strict conservation and sustainable management objectives and had a human population of 774,000 inhabitants as of 2010 (FVSA and WWF, 2017). As of 2019 there was an indigenous population of reportedly 10,218 inhabitants across 118 villages (IPEC, 2020). In the province of Misiones, drivers behind native forest losses are similar to those at the national level (e.g., agricultural expansion) but have also been attributed to industrial-scale forestry in the form of even-age plantations of eucalyptus and pine primarily for pulp and paper manufacturing (WWF, 2015).

Brazil has implemented environmental legislation to manage nearly 5 million km^2 of native forests including the Amazon and Paraná Atlantic Forest, representing 57.31% of its territory (MALFS, 2019). Environmental conservation and protection of biodiversity began to gain legislative prominence since the implementation of the National Law 4771 "Forestry code" (Portuguese: Código Florestal) in 1965 (Table 2). In the 1980's two landmark actions were implemented. The first was with the National Environmental Policy passed in 1981, and the second was with the promulgation of the Constitution of the Federative Republic of Brazil in 1988. Both addressed the importance of conserving Brazilian ecosystems and biomes. After 2015 there was a considerable decrease in deforestation rates compared to the previous 30 years. This noted decrease has been partly attributed to important monitoring partnerships, such as Fundação SOS Atlantic Forest and National Institute for Space Research – INPE (da Silva et al., 2016).

The year 1991 marked an important landmark when Brazil approved its first Atlantic Forest Biosphere Reserve (RBMA) through UNESCO. The reserve became what is the largest Biosphere Reserve on the planet, with 89,687,000 ha encompassing the Atlantic Forest Biome. In Brazil, the Paraná Atlantic Forest covers about 1,277,365 km^2 representing around 15% of the national territory spanning 17 states. About 8.2% of the Brazilian Paraná Atlantic Forest (109,783 km^2) are under some type of formalized protection category. The conservation of biodiversity within the Paraná Atlantic Forest ecoregion was stressed in the year 2000 when the National Law No. 9985 instituted the National System of Conservation Units (Portuguese: Sistema Nacional de Unidades de Conservação) and established criteria and norms for the creation, implementation, and management of conservation units.

In 2012, National Law No. 12.651 established a new Forest Code for the protection of native vegetation. The law aimed to regulate and preserve native forests with new focus on sustainable use and economic development. As of 2015, there were 915 officially registered conservation units in the Paraná Atlantic Forest ecoregion, with 818 located in Brazil, representing about 102,000 km^2 of forest under conservation (FVSA and WWF, 2017). The Paraná Atlantic Forest in Brazil has experienced high anthropization within 12.5% of its original cover, regularly in the form of small forest fragments (smaller than 1 km^2) and areas of high human population. This area is home to around 145 million people or about 70% of Brazil's population (da Silva et al., 2016).

In Paraguay, the Paraná Atlantic Forest covered about 85,770 km^2 at

Table 2
Landmark Brazilian legislation addressing native forest conservation, restoration of degraded areas and promotion of sustainable forest uses.

Enactment year	Number	Name	Citation	Brief description
1965	4771	Institutes forest code	Forest Code (1965)	Declaration of common interest: the forests in the national territory and other forms of vegetation.
1981	6938	Provides for the National Environment Policy	National Environmental Policy (1981)	Creation of the National Environment System (SISNAMA) and institutes the Environmental Defense Registry.
1988	Art. 225. Chapter VI §4° Federal Constitution of Brazil	Environment	The Environment (1988)	The Brazilian Amazon Forest, the Atlantic Forest, the Serra do Mar, the Pantanal Mato-Grossense and the Coastal Zone are national heritage, and their use will be made in the form of the law, within conditions that ensure the preservation of the environment, including the use of natural resources.
1991	–	Atlantic Forest Biosphere Reserve	UNESCO (2021)	Brazil approved with UNESCO, its first Atlantic Forest Biosphere Reserve – RBMA.
2000	Law 9985. Regulates art. 225, § 1, items I, II, III and VII of the Federal Constitution	National system of conservation units	National System of Conservation Units (2000)	Constitution, establishing the National System of Conservation Units and other provisions.
2006	Ordinances of the Ministry of the Environment, 349, 350 and 351	Mosaic of Conservation Units (CU)	Mosaic of Conservation Units (2006)	The project to support the creation of the Atlantic Forest mosaics was coordinated by the National Council of the Atlantic Forest Biosphere Reserve (RBMA)
2006	11428 Atlantic Forest Law	Provides for the use and protection of native vegetation in the Atlantic Forest Biome	Use and protection of native vegetation of the Atlantic Forest Biome (2006)	Declaration of a national heritage the Atlantic Forest and regulation for conservation, protection, regeneration, and uses of the Atlantic Forest.
2012	12651	Institutes New Forest Code	Protection of Native Vegetation (2012)	Provides for the protection of native vegetation; revokes Laws n° 4771, of September 15, 1965.

the dawn of the 20th century. As was the case in Argentina, land changes throughout the 20th century started with intense selective logging of hardwood species followed by conversion to cropland and/or pasture (Cartes, 2003; Chebez and Hilgert, 2003). Despite having a national legal framework preventing deforestation and promoting sustainable management and native forest conservation, Paraguay has the highest rate of deforestation in South America and is believed to have the second highest rate of deforestation in the world - only second to Indonesia (WWF, 2006b). A period of intense deforestation lasted from 1960 to 2001 when forests were considered as an obstacle to development as established by the Statute Agrarian of Paraguay. Changes in land use in the Paraná Atlantic Forest ecoregion (Eastern Paraguay) have been attributed to cattle grazing, and cropping of soybeans and cotton, among other commodities (FVSA and WWF, 2017).

In 1973, Paraguay implemented the national Forest Law (Spanish: "Ley Forestal") to regulate and promote the protection, conservation, sustainable use of native forests and to promote afforestation and reforestation activities (Table 3). Paraguay also implemented other legal tools at the national scale to prevent deforestation, promote conservation and restoration of degraded areas. For instance, in 2006 it implemented a national Program for Environmental Services through Law 3001 Valuation and Remuneration of Environmental Services (Spanish: "Valoración y Retribución de los Servicios Ambientales"). Paraguay has also implemented a normative instrument to avoid land use change since 2004 through Law No. 6256 "Zero deforestation" (Spanish: "Deforestación Cero").

At the same time, Paraguay has established 34 protected areas within the Paraná Atlantic Forest (FVSA and WWF, 2017). For instance, the Itaipu Biosphere Reserve was created in 2017 to protect 10,474 km^2 of remaining Paraná Atlantic Forest; this is an area with a permanent human population of over 450,000 inhabitants (UNESCO, 2017). The National Forest Inventory reports 191,000 km^2 of native forest (Instituto Forestal Nacional, 2015) where the remaining portion of Paraná Atlantic Forest in the Paraguayan side was estimated at 10,000 km^2 (Jaramillo et al., 2009). These forests are highly fragmented and degraded; however, still offer habitat to rare wildlife including large predators such as harpies (*Harpia harpyja*), crested eagles (*Morphnus guianensis*), jaguars (*Panthera onca*), pumas (*Felis concolor*), and large herbivores such as tapirs (*Hydrochaeris hydrocheris*), various deer species (*Mazama* sp.), and two species of peccaries (*Tayasu* sp.) among many others (UNESCO, 2017). Da Ponte et al. (2017) state that one of the main drivers of deforestation in Paraguay is the higher profitability of agricultural activities compared to forest conservation.

3. Methods

3.1. Data

We assembled a geospatial database in QGIS including sources of remotely sensed information on forest conditions and data at municipal and national levels for socio-economic information (Table 4). These were the most spatially explicit and current data sources available to us at the time of the study. We first compiled forest composition and subsequent loss from maps developed by Global Forests Watch (Hansen et al., 2013). These data provide and indicator for loss in forest cover within 25-by-25-m pixels modeled from Landsat TM imagery between the years 2000 and 2020. We restricted our sample to only pixels with forest cover as of the year 2000 determined by a canopy density criterion ≥25%, which is the most frequently adopted standard for forest designation using satellite imagery in this region (Ramírez et al., 2021). We further restricted our sample (Fig. 1) to samples identified as within the boundaries of the Paraná Atlantic forest ecoregions (Bailey, 2014).

Distances from each sampled pixel to the nearest road, port and city were measured based on their corresponding Euclidean distance using spatial data from OpenStreetMaps (Haklay and Weber, 2008) and Google Earth Imagery (2021). Our choice of various Euclidian distances stemmed from how they control for different market-access factors (e.g., distances to ports, cities, roads) and have empirically offered a combined better statistical goodness-of-fit than a single time-distance variable when studying deforestation in similar contexts (Salonen et al., 2014). Forest elevation and degree slope were calculated from a GOTOPO30 created by USGS and available in the Earth Resources Observation and Science Archive (Gesch et al., 1999). We identified the presence of forest protected areas by including a layer from the World Database on Protected Areas (IUCN, 2021). Percent change in population density was obtained from the Center for International Earth Science Information Network (CIESIN, 2017). The population density estimates are derived from a collection of high-resolution census data sources and disaggregated further using an area-based weighting method to provide population density estimates at a 30 arc-seconds per pixel scale. Spatially explicit "Gross Cell Product", developed by Geiger et al. (2017), provides per-pixel insight into economic growth between

Table 3
Paraguayan legal framework addressing native forest conservation, restoration of degraded areas and promotion of sustainable forest uses.

Enactment year	Number	Name	Citation	Brief description
1973	422	Forest Law	Forest Law (1973)	Declaration of public interest, the use and rational management of the forest and the protection, conservation, improvement, and enhancement of forest resources. Regulation of forest use and categorization of forest.
1992	96	Wildlife	Wildlife (1992)	Declaration of public interest in Wildlife, its protection, management, and conservation. Regulation of uses.
1993	251	Convention on “climate change” adopted during the United Nations conference	Climate change (1993)	Commitment to reduce and mitigate climate change and sustainable development activities.
1996	970	Struggle against desertification, in countries affected by the severe drought or desertification	Desertification (1996)	Commitment for sustainable management actions in arid, semi-arid and dry sub-humid zones.
1999	1561	Creates the national environment system, the national council of the environment and the secretary of the environment	Environment System (1999)	Preparation, standardization, coordination, execution and supervision of the national environmental policy and management.
2006	3001	Valuation and remuneration of environmental services	Environmental services (2006)	Promotion of the conservation, protection, recovery and sustainable development of the country’s biological diversity and natural resources.
2010	4014	Fire prevention and control	Fire prevention and control (2010)	Establishment of norms to prevent and control forest fires and prohibition of uncontrolled burning of forests.
2018	6256	That prohibits the activities of transformation and conversion of surfaces with forest coverage in the eastern region.	Land use change (2018)	Established restrictions on land use change with the goal of protecting and recuperating most of the native forest in the oriental region with the aim of achieving more sustainable development.

Table 4
Description of data used in the analysis of deforestation in South America’s Paraná Atlantic Forest.

Data	Description	Original data format and scale	Source
Forest cover	Time-variant identification of forest cover: 1 = Forested; 0 = Land change	Raster (Pixel: 30 × 30 m resolution)	Hansen et al. (2013)
Slope	Time-invariant continuous variable: Degree of slope	Raster (Pixel: 30 arc-seconds)	USGS EROS Center (2018)
Elevation	Time-invariant continuous variable (m): Meters above sea level	M.a.s.l., raster (Pixel: 30 arc-seconds)	USGS EROS Center (2018)
Political boundaries	Time-invariant country- and provincial-level boundaries: Categorical variables with baseline level	National/ provincial polygon shapefiles	CBI (2021)
Roads	Time-variant Euclidian distance to nearest road (Km)	Line shapefile	Haklay and Weber (2008)
Ports	Time-variant Euclidian distance to nearest port (Km)	Point shapefile	Google Earth Imagery (2021)
Designated forest protected areas	Time-variant legally recognized conservation areas; 1 = protected designation; 0 = Otherwise	Polygon shapefile	UNEP-WCMC (2019)
Population density percent change	Time-variant percent change in inhabitants/ km^2, between 2000 and 2020	Raster (Pixel: 30 arc-seconds)	CIESIN (2017)
Spatially explicit per-pixel Gross Domestic Product (GDP)	Time-variant percent change in the value of all goods and other market services provided to the rest of the world between 2000 and 2010 / km^2 Time variant estimates of population density.	Raster (Pixel: 30 arc-seconds)	Geiger et al. (2017)

2000 and 2010 as a function of changes in population density and national estimates of Gross Domestic Product.

This geospatial database was sampled using a balanced 1 km grid. The grid was comprised of a total of 242,571 sampled pixels for the total study area, with 14,164 samples located in Alto Paraná Paraguay, 29,921 samples in Misiones Argentina and 198,486 samples in Paraná Brazil. There were 112,401 data points included in our final dataset after removing pixels that fell outside of an ecological region identified as ‘forest’ and with canopy cover greater than or equal to 25% density as of the baseline year 2000.

3.2. Econometric analysis

Our analysis is premised on how the probability of land use change, from forests to non-forest uses as inferred from changes in canopy cover, is latently driven by land rent principles. Forestland's opportunity costs of alternative uses can create an incentive for conversion when expected rents exceed net present value for forest conservation (Zhang and Pearse, 2011). Land rent is directly a function of accessibility (Chomitz and Gray, 1996) which is captured by our various Euclidean distance variables and elevation. Designation of forests as a protected area for strict conservation partly aims to reduce land opportunity costs by outright preventing, or at least reducing, any potential rents from other land uses (Angelsen, 2010). Other interpretations exist such as a protected areas increasing transaction cost of timber harvesting and land conversion when penalties for violations are enforceable. Expected land rent is also affected by other exogenous factors such as population and international markets that can increase the opportunity cost of forest conservation. For instance, Leblois et al. (2017) and Cuaresma et al. (2017) found that increases in agricultural-based foreign trade was a major factor associated with deforestation.

Our systematic analysis for the probability of observed deforestation in a general form is given by:

$$\frac{Prob_i\ (Deforested)}{Prob_i(Forested)} = \frac{p(x_i)}{1-p(x_i)} = f\ (\text{land rent variables}) \tag{1}$$

denoting the odds of a sampled pixel classified as forested in 2000 keeping or not that same classification by 2010 and 2020. These odds are a function of a vector x of explanatory factors underlying the ith pixel (x_i) land rent. To estimate the systematic linear β associations of the odds of deforestation with the vector of explanatory variables with a random noise (ε) following a logistic distribution (Caliendo and Kopeinig, 2008) as:

$$log\frac{p(x_i)}{1-p(x_i)} = x_i'\beta + \varepsilon_i \tag{2}$$

We calculated odds-ratios for deforestation over continued forest cover by exponentiating β coefficients. The corresponding average percent change in odds was given by:

$$100 \times \left\{e^{(\beta)} - 1\right\} \tag{3}$$

We fit this logistic model for the odds of deforestation between the period 2001–2020, and select 10-year intervals, in Paraná Atlantic Forests in the provinces of Paraná, Brazil; Misiones, Argentina; and Alto Paraná, Paraguay. Explanatory variables georeferenced to the ith pixel were elevation, distance to nearest road, port, and city, protected area designation, population density, gross-domestic product. The model is linear in its coefficients, but we examine non-linear and non-monotonic associations when including all distance variables in quadratic form. Others (e.g., Van and Azomahou, 2007a, 2007b; Barber et al., 2014; Salonen et al., 2014; Ferraro et al., 2015; Cuaresma et al., 2017; Milien et al., 2021), have examined similar nuanced relationships with various distance specifications when estimating their associations with deforestation but localized analyses are limited, and none exist for our study area.

4. Results

Fig. 2 shows annual deforestation rates (%) for each of the three provinces along the primary vertical-axis (line chart), and total estimated native Paraná Atlantic Forest cover (Km^2) along the secondary vertical-axis (area chart). Results indicate overall deforestation rates of 20.1% in Paraguay's Alto Paraná, 18.4% in Argentina's Misiones, and 13.1% in Brazil's Paraná Department over our 20-year period of study. Highest annual deforestation rates occurred between 2001 and 2005 within the Alto Paraná where the rate peaked at just over 3% in 2004. By comparison the rate of deforestation in Brazil's Paraná and Argentina's Misiones remained relatively stable, at around 1% or below from 2001 until 2013, when Misiones began to experience a slight spike in deforestation. After 2013 the rates of deforestation among Alto Paraná and Paraná remained similar, but Misiones experienced around a 0.25% to 0.5% greater annual deforestation compared to Alto Paraná and Paraná between 2013 and 2019. The secondary vertical-axis in Fig. 2 shows the estimated total (Km^2) undisturbed forest area between 2000 and 2020. We estimate that Paraná (Brazil) accounted for the largest total area of primary forests among the three provinces with a total of 87,073 Km^2 in 2000. This area was estimated to lose about 11,309 Km^2 (12.98%) between 2001 and 2020. Misiones, Argentina was estimated to have a total

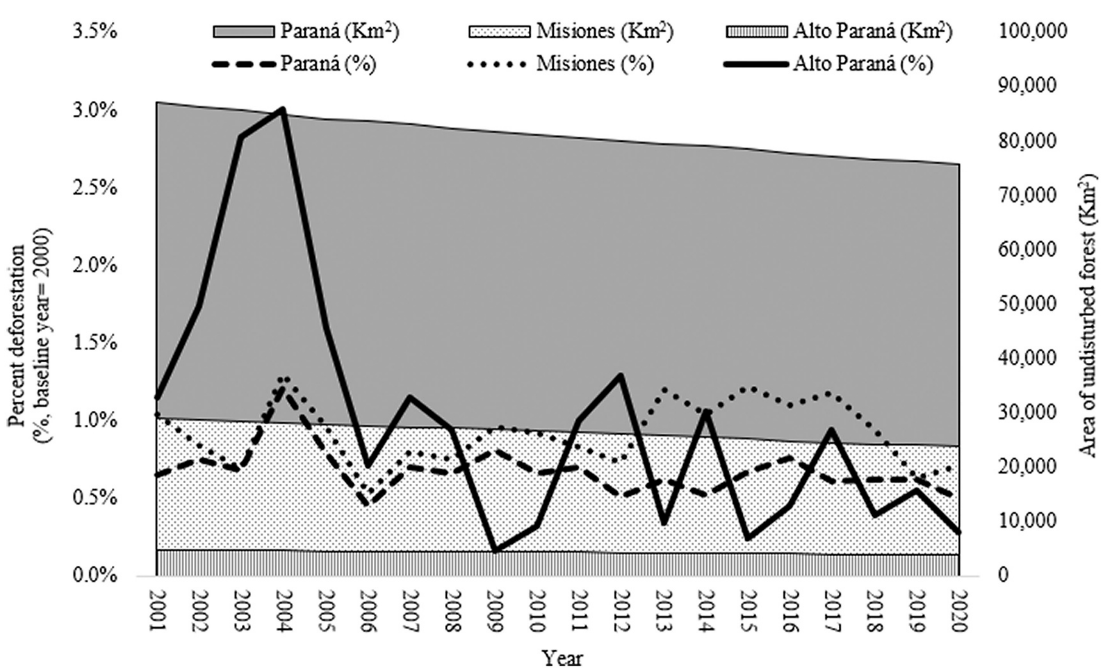

Fig. 2. Annual deforestation rates and remaining undisturbed forests, by province (Alto Paraná, Paraná, and Misiones).

of 28,944 Km^2 as of 2000 and lost 5076 km^2 (17.54%) by 2020. Alto Paraná (Paraguay) had the smallest total area of intact forests with an estimated 4830 Km^2 as of 2000 and lost 843 Km^2 (17.45%) by 2020.

Table 5 shows results of the logistic regression for the odds of deforestation for the three modeled periods: 2000–2010, 2010–2020, and 2000–2020. There is evidence of strong statistical significance for all our main explanatory variables and our overall model fitness. There is consistency in the direction and overall magnitude of estimated coefficients, but differences exist, particularly in the intensity of deforestation. For instance, we found statistically significant heterogeneity in the designation of protected areas across provinces. Consistently, all three models show an inverse relationship between slope and the odds of deforestation. On average the odds of deforestation were lowered by 5.73% to 7.50% with every degree increase in slope. A similar association has been reported in the clearing of forest dominated lands by Blackman et al. (2008, 2012) in Central America and in central Ecuador (Mohebalian and Aguilar, 2016). Estimated elevation was also a significant determinant of deforestation in all three models, with the odds of deforestation increasing by an average 0.01% for every single meter increase in elevation.

Estimated effects of proximity to roads, ports and cities are more nuanced, and are plotted in Fig. 3. Overall, distance to nearest road showed consistent signs with the odds of deforestation following a convex trajectory between 2000 and 2010, and between 2000 and 2020. During these periods, coefficients suggest that the odds of deforestation were lower with longer distances from nearest road with an inflexion point at ~10Km; i.e., odds of deforestation declined with longer distances from the nearest road up to ~10Km when the relationship reversed, and odds of deforestation tend to increase over longer distances. Others have reported an overall linear association with coefficients denoting proximity to transportation networks (e.g., Barber et al., 2014; Mohebalian and Aguilar, 2016; Milien et al., 2021) but we identify a more nuanced relationship. Proximity to roads eases accessibility and could increase the likelihood of deforestation. Here, we find that, although accessibility may be challenging, beyond a certain distance the likelihood of deforestation increased significantly. A possible explanation backed by casual observation is that illegal deforestation tends to avoid too close proximity to roads to evade detection and possible penalties. Hence, permanent land change to uses such as grazing tends to become more likely beyond 10 Km.

The linear coefficient for Euclidean distance to nearest city was found not to have a statistical effect during the 2000 to 2010 period. The terms for distance to nearest city indicated statistically significant monotonic effects showing higher odds of deforestation further away from cities during the 2010 to 2020 and 2000 to 2020 periods. On average, farther distances to city resulted in 0.05% and 0.08% higher odds of deforestation. This association is congruent with findings by Salonen et al. (2014) in the Brazilian Amazon, among many others. A plausible explanation for the lack of statistical significance for the first decade might be how initially high deforestation was ubiquitous across our entire study area. Localized effects, nonetheless, were captured in our other distance variables. Such is the case of distance to nearest port, which showed consistent directional associations and the odds of deforestation increasing at a slightly increasing rate. Overall, deforestation pressures heightened away in locations of lesser accessibility, where policy instruments are often difficult to monitor and enforce.

The change in per-pixel-adjusted GDP between 2000 and 2010 was also found to be statistically significant. A 1% increase in per-pixel GDP was associated with 0.1% higher odds of deforestation between 2000 and 2010, and 1.1% higher odds of deforestation between 2010 and 2020. Overall, between 2000 and 2020 a 1% increase in per-pixel GDP was associated with 0.9% higher odds of deforestation. The percent change in population density of a province had a positive relationship with deforestation. In all three models, a 1% increase in population density was associated with 0.2% higher odds of deforestation. Results indicating a positive relationship between change in per-pixel GDP and

Table 5
Results of logistic model of the odds of deforestation in the Paraná Atlantic Forests (2000–2020).

Explanatory variables	2000–2010 (n = 112,401)					2010–2020 (n = 112,915)					2000–2020 (n = 121,784)				
	Coef.	Odds Ratio	%Δ O.R.	S. E.	p-value	Coef.	Odds Ratio	%Δ O.R.	S. E.	p-value	Coef.	Odds Ratio	%Δ O.R.	S. E.	p-value
Slope (degrees)	−0.078	0.925	−7.504	0.009	<0.001	−0.059	0.942	−5.729	0.008	<0.001	−0.069	0.933	−6.667	0.006	<0.001
Elevation (m.a.s.l.)	0.001	1.001	0.100	<0.001	<0.001	0.001	1.001	0.100	<0.001	<0.001	0.001	1.001	0.100	<0.001	<0.001
Distance from roads (Km)	−0.014	0.986	−1.390	0.003	<0.001	−0.013	0.987	−1.292	0.004	<0.001	−0.014	0.986	−1.390	0.003	<0.001
Distance from roads, squared (Km^2)	0.001	1.001	0.100	<0.001	<0.001	0.001	1.001	0.100	<0.001	<0.001	0.001	1.001	0.100	<0.001	<0.001
Distance from cities (Km)	0.001	1.001	0.100	0.001	0.177	0.008	1.008	0.803	0.001	<0.001	0.005	1.005	0.501	0.001	<0.001
Distance from cities, squared (Km^2)	<0.001	1.000	<0.001	<0.001	0.013	<0.001	1.000	<0.001	<0.001	<0.001	<0.001	1.000	<0.001	<0.001	<0.001
Distance from ports (Km)	0.007	1.007	0.702	<0.001	<0.001	0.005	1.005	0.501	<0.001	<0.001	0.006	1.006	0.602	<0.001	<0.001
Distance from ports, squared (Km^2)	<0.001	1.000	<0.001	<0.001	<0.001	<0.001	1.000	<0.001	<0.001	<0.001	<0.001	1.000	<0.001	<0.001	<0.001
Percent change in population density (Inhabitants per Km^2)	0.002	1.002	0.200	<0.001	<0.001	0.002	1.002	0.200	<0.001	<0.001	0.002	1.002	0.200	<0.001	<0.001
Change in gross cell product (%)	0.007	1.007	0.702	0.001	<0.001	0.011	1.011	1.106	0.002	<0.001	0.009	1.009	0.904	0.001	<0.001
Protected designation†	−0.760	0.468	−53.233	0.057	<0.001	−0.607	0.545	−45.502	0.049	<0.001	−0.670	0.511	−48.829	0.038	<0.001
Protected designation: Alto Paraná‡	−3.198	0.041	−98.090	0.995	0.001	−11.242	<0.001	−99.999	46.276	0.808	−3.648	0.026	−98.667	0.994	<0.001
Protected designation: Misiones‡	−2.660	0.070	−96.729	0.155	<0.001	−2.803	0.061	−96.696	0.165	<0.001	−2.747	0.064	−96.719	0.114	<0.001
Alto Paraná	0.725	2.064	106.473	0.074	<0.001	−0.068	0.935	−6.574	0.084	0.422	0.411	1.508	50.833	0.057	<0.001
Misiones	0.844	2.326	132.565	0.051	<0.001	0.472	1.603	60.320	0.048	<0.001	0.690	1.993	99.372	0.037	<0.001
Intercept	−4.121	0.016	−98.377	0.102	<0.001	−4.435	0.012	−98.814	0.105	<0.001	−3.610	0.027	−97.295	0.076	<0.001
Log-likelihood ($p > Chi^2$)	−28,021	(<0.001)				−29,581	(<0.001)				−46,327	(<0.001)			
McFadden's R^2	0.067					0.054					0.067				

†Base line level: Brazil's Paraná forests under protected designation. ‡ Specific %Δ O.R. for Alto Paraná and Misiones estimated after summation of baseline protected designation coefficient and province-specific interaction term (e.g. Protected designation × Alto Paraná).

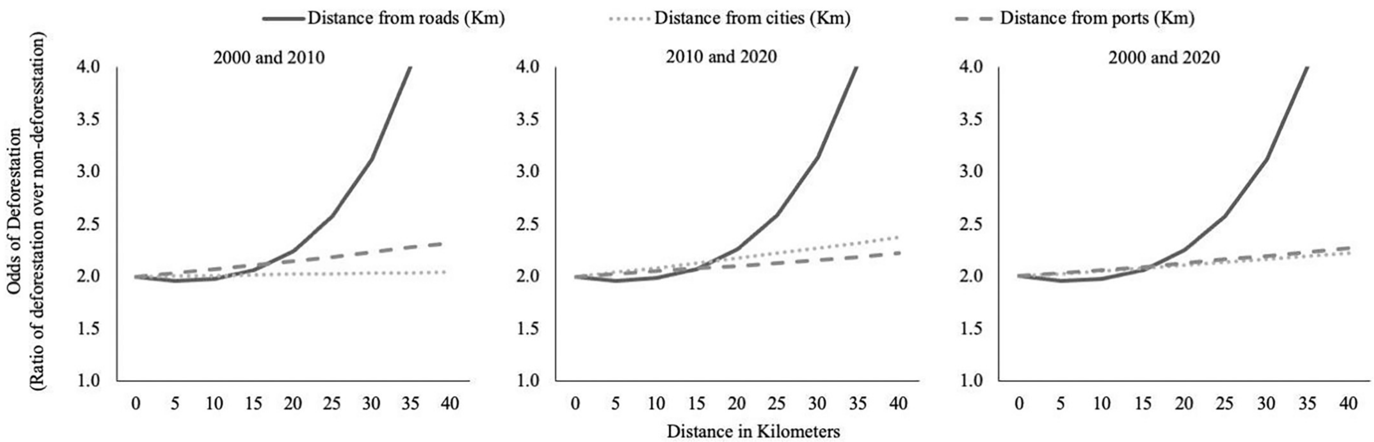

Fig. 3. Estimated odds of deforestation associated with Euclidean distances to nearest road, city, and port.

population density, and higher odds of deforestation are consistent with Geldmann et al. (2019), among others. These sets of variables partly captured increased deforestation pressures driven by higher opportunity costs of forgone agricultural activities. While legislation has attempted to address this issue, it may not be sufficient. For example, in 2022 the Argentinean government allocated 3% of its national budget to Forest Law 26331 for conservation. As a result, forest landowners can receive 0.25 US$ per year for each hectare of native forest under conservation. But the same hectare of land, if converted to corn or soybean production could provide the owner about 290 US$ per year on average.

The province where the forest was located was also found to have a statistical effect on deforestation odds. Else constant, forests located in Argentina's Misiones were found to have 1.6 to 2.3 times higher odds of deforestation than forests in Brazil's Paraná. Forests in Paraguay's Alto Paraná had 2 times higher odds of deforestation between 2000 and 2020, but 6% lower odds of deforestation between 2010 and 2020, compared to forests in Brazil's Paraná.

Protected area designation showed the greatest association against the odds of deforestation. Over our entire 2000–2020 period, a protected designation was associated with 48.83% lower odds of deforestation in Brazil's Paraná, 98.67% lower odds in Paraguay's Alto Paraná, and 96.72% lower odds in Argentina's Misiones. Forests with protected area designation were 53.23% less likely to be deforested, than non-designated lands, in Brazil during the 2000–2010 period. Respective values in Argentina and Paraguay were 96.73% and 98.09% during the same period. Over the 2010–2020 period the observed reduction in the deforestation rate associated with protected designation decreased to 45.5% in Brazil and remained stable at 96.69% in Argentina and 99.99% in Paraguay. Overall, such associations are in line with past policy reviews for Latin America (Chomitz et al., 2007) and assessments in Brazil of overall forest cover change within conservation areas (e.g., Barber et al., 2014; Milien et al., 2021). We should note that evidence of avoided deforestation points to effectiveness of protected area designation, conservation initiatives can also yield benefits beyond undisturbed canopy cover terms of avoided deforestation by preventing the extraction of species of commercial timber value (Mohebalian and Aguilar, 2018; Eguiguren et al., 2019). Hence, the actual benefits as reported here might be conservative in terms of protecting the integrity of tropical forest ecosystems.

All three countries in the Paraná Atlantic Forest region of South America have made significant legal strides toward the sustainable development of forest resources, yet differences in strategies have been observed. Currently in the Paraná Atlantic Forests of Paraguay and Argentina, strict command and control laws have been instituted prohibiting land use change and restricting deforestation. In Paraguay this occurred partly because of Environmental Law 6256 of 2018 that prohibits the transformation of forests in the Eastern region of the country. In Argentina this was enacted in 2007 via law 2633 which established minimum budgets for environmental protection of native forests and oversite restricting loss of native forests in the country. Brazil has yet to develop strict laws regulating the loss of Paraná Atlantic Forest in the region. These actions might explain the differences found in our model. Within the estimation of heterogenous associations in protected designation between countries, it is also worth noting the need for future assessments that infer the social and economic impacts of strict conservation designation. This line of investigation seems even more relevant as population density and corresponding land utilization pressures increase to sustain local livelihoods.

5. Conclusions and recommendations

South America's Paraná Atlantic Forests hold one of the greatest levels of biodiversity globally but face tremendous deforestation pressures. Our review of public policy interventions shows that in the face of land-change pressures the governments of Argentina, Brazil and Paraguay have taken significant legislative steps toward protecting remaining Paraná Atlantic Forests. Among these tools, the adoption of protected areas and budget lines to finance them is one of the most common. Nevertheless, alternative land uses such as agriculture and pasture are common activities surrounding protected areas and have reportedly increased conversion pressures on remaining forests in all three countries. Albeit effective in lowering associated odds of deforestation as we report, increasing rents from land conversion might partly explain why existing legal policy instruments alone may not be sufficient the offset opportunity costs of conservation.

Accessibility, which affects land rent, and the difficulty of monitoring and enforcing conservation compliance, was closely associated with the odds of deforestation. We found that Euclidean distances to roads, cities, and ports were strongly associated with deforestation and included nuanced relationships. Distance to nearest road exhibited a convex association, and distance to cities and ports resulted in positive monotonic relationships over our entire study period. Forests with increased population density and growth in expected land-use value showed significantly greater deforestation pressures. Our results show that forest protected areas between years 2000 and 2020 effectively lowered the odds of deforestation in Paraná Atlantic Forests. Conservation policy laws such as the National System of Conservation Units in Brazil played an important role in establishing and maintaining forest protected areas in the region. We found highly heterogeneous country-level associations in odds-ratios at an average of 96.72% in Argentina, 48.83% in Brazil, and 98.67% in Paraguay.

While conservation initiatives have made significant strides in preventing the loss of Paraná Atlantic forests, we recommend a greater priority be placed in shaping future policy with a better understanding of the opportunity costs of land use conversion. For instance, future policy could benefit from strategies applying market-based approaches to conservation by targeting deforestation-prone areas. Greater impacts of forest conservation designation could be achieved by considering and addressing the economic incentives that catalyze land use conversion. as well the economic value of the services which forest ecosystems provide.

We recommend two specific areas for future research. First, we recognize that our findings are limited to associational inferences by virtue of the data available at the time of this study. A causal effect of the designation of protected areas across Paraná Atlantic Forests should be robustly tested. Differences from our results can be expected and we stress the importance of testing for heterogeneous effects of such policy interventions. On a second point, while the abundance of remote sensing imagery has allowed progress in the monitoring of forest conservation, an over reliance of remote sensing data has left a gap in assessing anthropogenic impacts on forest degradation. More granular data that can allow the assessment of ecological and socio-economic impacts of protected designation in Paraná Atlantic forests should be investigated. Within a more granular analysis of spatial data, other relationships occurring at smaller-spatial scales inclusive of social and economic impacts at household and village levels should be explored.

Author statement

Phillip M. Mohebalian: Conceptualization, Methodology, Data curation, Visualization, Writing; Lucas N. Lopez: Conceptualization, Methodology, Data curation, Writing; Angela Bárbara Tischner: Methodology, Data curation, Reviewing; Francisco X. Aguilar: Conceptualization, Methodology, Writing, Reviewing and Editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The views expressed in this paper are those of the authors and not those of their respective organizations or institutions

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