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Original Research Article

Chaco region: Forest loss and fragmentation in the context of the territorial planning law. Remote sensing assessment in Formosa, Argentina application case

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ABSTRACT

Agricultural expansion is the primary cause of forest loss and fragmentation. It threatens the conservation of its biodiversity as well as the capability to provide ecosystem services. Land-use policies, such as zonation programs, have been traditionally used as a tool for promoting a sustainable natural resource management; however, we still lack standardized methodologies that can be applied world-widely to achieve this purpose. In the current context of rampant deforestation over the tropical forests, there is an urgent need of identifying policies that steer agricultural land-use change into a reduced pressure on forests. This study focuses on the outcomes of the first territorial planning law in the Province of Formosa (Argentina) located within the Chaco region, one of the world's deforestation hotspots. The research questions were: a) How did agriculture expand in Formosa before, during and after the enactment of the territorial planning law? b) Did the introduction of the law affect the spatial distribution of land-use change?; and c) How did the sanction of the law affect forest loss and forest fragmentation? Landsat imagery was used to map land-use change, and to calculate the cover loss and cover loss rate considering the zoning and physiognomic classification of the law. The forest fragmentation was evaluated in terms of forest loss spatial configuration, classified as perforation or shrinkage, forest edge generation, patch size distribution, and patch isolation. The territorial planning law effect over agricultural expansion was tested using a difference in difference model. After the law was passed, a reduced land-use pressure was observed for the forest within the conservation designated zone; however, the forest presented the highest cover loss rates among the physiognomic categories of the law. Land-use change within the conservation designated zone was predominantly made according to a perforation spatial configuration, which promoted the forest edge generation. The isolation between forest patches decreased and its size distribution changed towards a less large-patch-centered pattern, indicating that Formosa is experiencing an early fragmentation process. Overall, the territorial planning law in Formosa succeeded in the relief of land-use pressure on forest, but highlighted the need of incorporating spatial configuration guidelines for long-term forest conservation. The case of Formosa case could be useful in the design of future sustainable natural resource management policies and implies the importance of early natural resource planning.

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1. Introduction

One of the main human activities causing the loss and fragmentation of natural environments is agricultural expansion, i.e. the conversion of non-agricultural lands to agricultural lands, for example, the conversion of forested lands to crops, wetlands to paddy fields or fishponds, or natural grasslands to pastures (Qi, 2014). This activity is considered one of the main problems affecting the conservation of biodiversity (Foley et al., 2005; Kehoe et al., 2017) since it not only affects the fauna (Núnez-Regueiro et al., 2015; Pfeifer et al., 2017) and vegetation (Aguilar et al., 2006; Fahrig, 2018; Fischer and Lindenmayer, 2007; Torrella et al., 2013), but it also leads to soil erosion, acidification, and leaching of nutrients (Hu et al., 2021; Peters et al., 2011), thus deeply affecting the capability of a natural environment to provide its ecosystem services (Kettle and Koh, 2014; Vandermeer and Perfecto, 2007). In Western Europe, the effects of farming during Roman times in forest soil nutrient availability and plant diversity can still be measured almost 2000 years later, indicating that the effects of agricultural activity on this ecosystem may be irreversible on a historical time scale (Dupouey et al., 2002).

Forests are essential for human existence since they provide multiple benefits to a multitude of users (Millennium Ecosystem Assessment (Program), 2005). An example of this is its importance in the conservation of water and soil resources, as well as the provision of timber and non-timber resources (Sirya, Cubbage, and Ahmed, 2005). During 2001–2015 most of the global forest loss was caused by human activities, being the main causes of deforestation related to commodity production (27%, i.e. long-term, permanent conversion of forest to nonforest land use such as agriculture, mining, or energy infrastructure), forest loss due to forestry land-use (26%, i.e. large-scale forestry operations occurring within managed forests and tree plantations with evidence of forest regrowth in subsequent years), and shifting to agriculture (24%, i.e. small- to medium-scale forest conversion for agriculture that is later abandoned and followed by subsequent forest regrowth) (Curtis et al., 2018). FAO (2020) reported that forest loss is primarily caused by agricultural expansion.

Despite the fact that there has been a growing awareness of the role forests play in maintaining the ecological, climatic, economic, and social balances of the planet (Assembe-Mvondo, 2009; FAO, 2011, 2016), the development of effective policies and strategies to conserve this natural environment is complicated, and this striving is sharper in developing countries (Owubaha et al., 2001). In addition to this, the potential conflict situations arising from the multiplicity of existing users could cause a misuse of the resource (Kishor and Belle, 2004). Traditionally for sustainable land-use purposes, governments have relied on a mix of policies which includes command-and-control tools that directly affect land-use (i.e. zonation programs with differential resource use) and tacks associated with land-based activities (e.g. Reduced-impact logging techniques, RIL) (Lambin et al., 2014).

In the tropics, where most of the recent deforestation has occurred (Curtis et al., 2018; FAO, 2018; Graesser et al., 2018; Kim et al., 2015; Leblois et al., 2017), land-use zoning programs have been used as a tool to conciliate conservation and exploitation activities, albeit their results are diverse and strongly dependent on each case characteristics (Bruggeman et al., 2015, 2018; Camba Sans et al., 2018). Furthermore, there is an ongoing discussion on whether such policies should be centralized or decentralized (Andersson et al., 2006; Nolte et al., 2017). However, the idea of creating world standardized methodologies is complicated, since their design relies on the specific social, economic, and resource status conditions of the region in question, as well as the scale at which objectives are set. Moreover, policies are also unequal in their toughness and implementation, making empirical evidence of their effectiveness canonical to underpin future resource conservation approaches (Gaveau et al., 2009; Miteva et al., 2012), especially regarding the actual global crisis, where ecological environment degradation has become the constriction limiting further social development (Deboudt et al., 2008).

Within the tropics, Latin America has the world's largest agricultural land reserves and has had the fastest agricultural expansion during the twenty-first century (Graesser et al., 2018) due to the widespread deforestation for cattle ranching and soybean cultivation (Baumann et al., 2016; Gasparri et al., 2013; Graesser et al., 2018; Leblois et al., 2017). Although there have been some cases in which deforestation rates have been reduced by management policies in Amazonia (West and Fearnside, 2021), deforestation has been relentless in adjacent regions like Cerrado and Chaco region (Baumann et al., 2016; Graesser et al., 2018).

The Chaco region contains the most extensive forest masses of the continent after the Amazon. About 62.2% of the region belongs to the Argentine Republic and occupies 23.9% of the country's total territory (TNC, 2005). Over 9.6 million hectares of native natural environments, mainly forest, have been transformed (Ginzburg, 2019) as a consequence of this escalating agricultural expansion (Boletta et al., 2006; Carnevale et al., 2007; Gasparri and Grau, 2009; Hoyos et al., 2012; Vallejos et al., 2015; Volante et al., 2012; Zak et al., 2004). Since 1990 there has been a displacement of this agricultural expansion towards the semi-arid portion of the region attributable to the relative increase in rainfall and the incorporation of new technologies such as direct sowing and genetically modified crops (Adámoli et al., 2011). Furthermore, an important part of the land-use change has been made due to the incorporation of forage pastures implanted in livestock establishments (Volante et al., 2015). As a result, the Argentine Chaco region is one of the areas with the highest rates of deforestation in Latin America (Grau et al., 2008) and in the world (Hansen et al., 2013).

The aim of this study was to assess the outcome of the first land-use zoning policy in terms of forest loss and fragmentation for the province of Formosa, Argentina located in the Argentine Chaco. Formosa is a particular case because a) the enactment of its first territorial planning program was carried out under a context of low levels of land-use change; b) this policy matched the recent growth of agricultural activities in the province; c) the zoning encompasses the whole extension of the province; and d) the fact that Formosa is located within one of the world's deforestation hotspots. All these characteristics positioned Formosa as an opportunity to evaluate the results of a natural resource management policy under the context of planning prior to its exploitation and an upcoming high land-use pressure.

There is literature that addresses the province of Formosa in terms of the Argentine National Forest law (Aguiar et al., 2018;

Piquer-Rodríguez et al., 2018a; Vallejos et al., 2021) or regarding forest loss and fragmentation (Piquer-Rodríguez et al., 2015, 2018b; Vallejos et al., 2015). However, most of these publications address the dry portion of the province or include Formosa as part of a pan-Chaco analysis. This is one of the few studies that exclusively focus on Formosa and its Territorial Planning Provincial law. The research questions to assess the outcome of Formosa's territorial planning policy, at the regional scale, over the forest loss and fragmentation process, were:

a. How did agriculture expand in Formosa before, during and after the enactment of the territorial planning law?
b. Did the introduction of the law affect the spatial distribution of land-use change?
c. How did the sanction of the law affect forest loss and forest fragmentation?

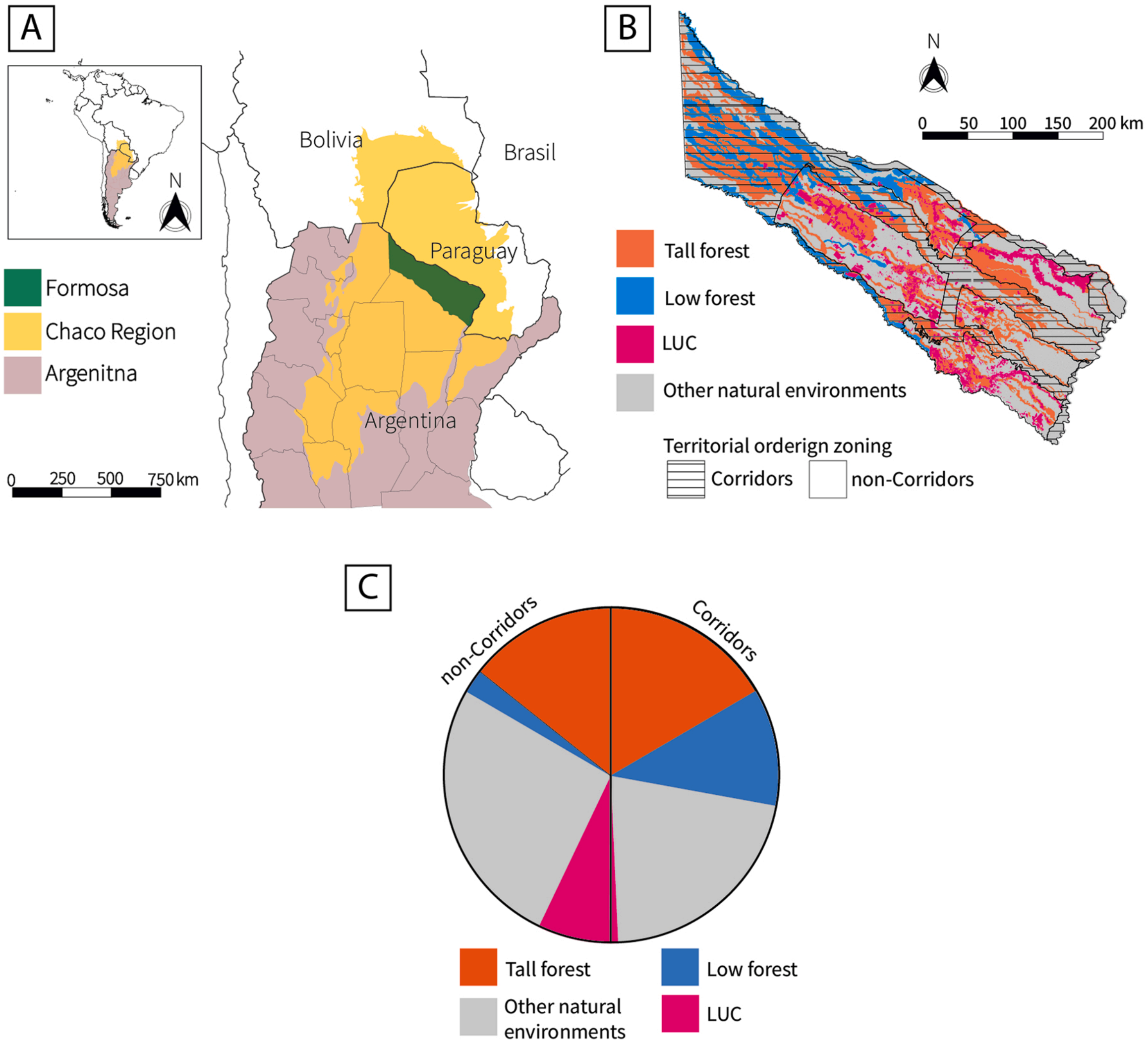

Fig. 1. A. Province of Formosa (green), Argentina within the Chaco Region (yellow). B. Natural land cover classification of the province of Formosa in 2010 according to the physiognomic groups established by TP Provincial law: tall forest (orange), low forest (blue), other environments (gray). The TP zoning is also shown: Corridors (striped) and non-Corridors. As well as the land-use change (LUC, magenta). - C. Distribution of total land-use change (LUC, magenta) and natural land cover of the province of Formosa in 2010 by the TP zoning: Corridors and non-Corridors. The natural environments are classified according to the physiognomic groups established by TP Provincial law: tall forest (orange), low forest (blue), and other natural environments (gray). For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

2. Materials and methods

2.1. Study area

2.1.1. Background

Agricultural expansion in the Argentine Chaco has not been equally distributed among the provinces that constitute this region. By the year 2008, most of it was concentrated in Santiago del Estero, Salta, Chaco and Córdoba (30%, 15%, 18% and 16% approx. respectively) (Ginzburg, 2019). Formosa, on the other hand, only accounted for 4%. This contrasting situation substantially responds to the recent arrival of medium-large agribusinesses in 2010 to Formosa and to the fact that soybean has not been a dominant crop within the province since almost half of its territory belongs to the Dry Chaco subregion (i.e. it has a deficit of precipitations for rainfed crops) and the remaining part overlaps with the Humid Chaco subregion covered by wetlands and floodable soils (Adámoli et al., 2011).

In terms of management, despite the fact that natural resources are decentralized in Argentina, the federal government has the power to determine minimum standards for natural resource protection. At the end of 2007, within this context of a rampant expansion of the agricultural frontier, the National Forest law was enacted (National Law No. 26.331, 2007) and all land clearing authorizations were suspended until the provinces classified their forest into three "conservation values'' categories (from high to low: red, yellow and green) with differential land-use restriction. In Formosa, the passage of the National Forest law coincides with its first territorial planning program, the Territorial Planning Provincial law (Provincial Law N° 1552, 2010) established in May 2010. The provincial law aimed to ensure the continuity between the different natural environments favoring their conservation, at a regional scale, and to designate areas for future productive development. The proximity between the enactment of the National and the Provincial law resulted in new land clearings projects, once the suspension was lifted, to be evaluated under the conjunction of both laws.

2.1.2. Formosa

This study included the entire province of Formosa, located in the north of Argentina within the Chaco region (Fig. 1 A). The province has an area of 7,574,785 ha, with a population of 579,280 inhabitants (INDEC, 2015). It has a tropical climate, presenting a range of rainfall that goes from 500 mm in the West of the province (within the Dry Chaco subregion) to more than 1200 mm in the East (within the Humid Chaco subregion). Formosa has three main rivers, the Bermejo which defines the southern border with the province

Table 1
Detailed elements of Formosa Territorial Planning Provincial law showing the established physiognomic groups and zoning policy. For each law element, **bold** font indicates categories within each element, normal font corresponds to definitions, and *italic* font denotes restrictions.

Main physiognomic groups established by TP Provincial law		
"Tall forest" (bosque alto).	"Low forest" (bosque bajo).	Other natural environments.
Primary forests settled besides the rivers or on riverbanks. It has deep and high organic matter soils; includes among others the Quebrachales.	Forest located in interfluves of less developed soils, with fewer species and less density than tall forests; forest mainly dominated by *Prosopis sp*.	Includes savannas, shrubs, grasslands, estuaries, and lagoons.
Zoning policy		
Corridors zone.		**Non-Corridors zone.**
It includes and connects the areas of greatest interest for the conservation of biological diversity (Biosphere Reserves, National Parks, other reserves, and Important Bird Areas). It has a low urban population and a low density of cultivated areas.		It contains the main agricultural core, the main urban centers, routes roads, grain storage, and processing facilities. The installation of future agricultural activities areas is mainly encouraged in this zone.
Up to 20% of the area within a single property can be transformed.		*Up to 60% of the area within a single property can be transformed.*
Maximum % of transformation allowed within the zone: • 10% of tall forest. • 60% of low forest. • 60% of other natural environments.		*Maximum % of transformation allowed within the zone:* • 60% of tall forest. • 60% of low forest. • 10% of other natural environments.

of Chaco, the Pilcomayo in the north, and the Paraguay in the east delimiting the border with Paraguay. Formosa's production is predominantly foraging pastures but it also has strong participation of the fruit-horticultural sector, cotton, and rice (Gobierno de la Provincia de Formosa, 2015).

2.2. Territorial planning policy details

Formosa's Territorial Planning Provincial law, enacted in 2010, aims to promote sustainable natural resource management at a regional scale by ensuring continuity between the different natural environments, favoring their conservation, and by designating areas for future productive development. For this purpose, the province is divided into two zones: *Corridors* and *non-Corridors*, and each one is assigned a maximum allowable percentage of land-use change. The law also classifies all the natural environments into three large physiognomic groups and restricts its transformation according to the zone (Fig. 1B; Table 1), considering simultaneously the categories and regulations of the National Forest law. The land-use change restrictions are imposed at a plot scale to facilitate their application although the purpose of the provincial law is set at a regional scale.

Formosa was the only province that included the National Parks Administration proposal and implemented the strategy of conservation corridors in its territory. This strategy consisted in creating a network of protected areas interconnected and contained by an ecological corridors matrix. The matrix encompasses natural corridors associated with the great rivers (Bermejo, Pilcomayo, Paraguay, and others) and their associated forest, which crosses several provinces. The goal was to guide the territorial planning of the Argentine Chaco region by helping to conciliate its development and conservation (APN, 2006). Formosa modified this proposal so that it included, besides protected areas, almost all the Important Bird Areas (i.e. places of international significance for the conservation of birds and other biodiversity; Di Giacomo, 2005) and 75% of the surface of the aboriginal communities. In this way, half of the provincial territory is defined as a corridor zone (Fig. 1C).

2.3. Data analysis

2.3.1. Land-use change mapping

To evaluate the land-use change (LUC) process of the province of Formosa in recent years, four years were analyzed: 2001, 2008, 2010, and 2015. The year 2008 represents the enactment of the National Forest law, whereas 2010 corresponds to the passage of the Territorial Planning Provincial law.

The mapping of transformed areas was carried out for the entire province of Formosa for each one of the selected years. The study area consists of 8 Landsat images obtained from USGS (US Geological Survey, USA). For 2001 the mission used was Landsat 7 ETM + (bands: 4–5–2), for the years 2008 and 2010 it was Landsat 5 TM (bands: 4–5–2) and for 2015, Landsat 8 OLI/TIRS (bands: 6–5–3). RGB false-color composite images were assembled and interpreted with QGIS 2.8 Wein.

From the composite images, all the plots in which the original vegetation cover had been replaced by crops, both agricultural and pasture were visually identified and mapped at a scale of 1:250,000. The visual classification was based mainly on the color and shape characteristics; the cultivated plots usually have a Fluor pink-green hue (under the composition of the selected bands) and well-defined edges (Fig. 2).

The accuracy assessment for the land-use mapping was conducted for the entire 2001–2015 data set; the methodology was adapted from Baldassini et al. (2012). A total of 300 random points were created, 150 within the transformed area polygons with a minimum distance of 3 km between points, and 150 outside the mapped polygons with the same spatial restriction. Google Earth Pro® images were used to evaluate whether these points corresponded or not to a transformed area. In case there was no available image from Google Earth Pro for a given point, another random point was created to replace it. The global accuracy calculation was based on the contingency matrix.

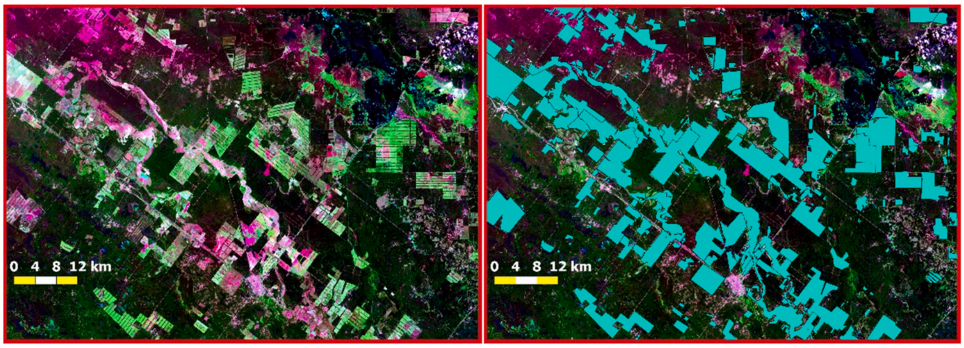

Fig. 2. QGis software transformed area mapping illustration. A Satellite image showing unmapped transformed areas (left) and a satellite image showing mapped transformed areas (right). For interpretation of the references to color in this figure, the reader is referred to the web version of this article.

2.3.2. *Land-use change over natural environments*

The same two vegetation maps employed by the province for the enactment of the law were used for the study of the LUC over the physiognomic groups defined in the TP Provincial law. Said maps were the vegetation map especially created for the provincial law itself, which distinguishes forest from other natural environments, and the Formosa's vegetation map for the year 2006 by Adámoli et al. (2008), which separates Tall Forest from Low Forest. With both maps, following the methodology of Adámoli et al. (2008), a vegetation map of Formosa was recreated for the year 2001. This methodology consists of identifying and mapping, at a 1:250,000 scale, the vegetation units by their dominant physiognomy and the assignment of preexistent LUC to the vegetation units based on their location, i.e. within which unit it is immersed and/or adjoined. In the present study, only the classification of preexistent LUC was made. Once the map of 2001 was recreated, a successive overlapping of the LUC was made for each year analyzed. In this way, a map of natural environments with their transformed areas was obtained for the years 2001, 2008, 2010, and 2015. This allowed calculating the LUC areas and loss rates of the different physiognomic groups for each period, e.g. the data for the period 2001–2008 was based on the difference between the map of 2001 and 2008. The loss rates were calculated according to the Puyravaud (2003) equation and multiplied by 100 for a more convenient reading:

$$r = \frac{1}{(t_2 - t_1)} \times \ln\frac{A_2}{A_1}$$

A_1: natural environment cover at the beginning of the period.
A_2: natural environment cover at the end of the period.
t_1: start year of the period.
t_2: end year of the period.

Since the loss rates are based on the same methodology used by the Management Unit of the Forest Assessment System of the Secretariat of Forests of the Ministry of the Environment of the Nation (UMSEF, 2015), they can be compared with the loss rates recorded by other provinces, as well as by other regions of the globe (Chicas et al., 2017; Locher et al., 2017).

2.3.3. *Territorial Planning Provincial Law effect on different natural environments*

The natural environments created map for each year was crossed with Formosa's territorial planning zoning map, resulting in a series of maps in which the province natural environments were classified according to the law categories: "tall forest" (TF-TP), "low forest" (LF-TP) and Other natural environments (OE-TP), and the zoning: *Corridors* and n*on-Corridors* zone (Fig. 2.). The LUC areas and loss rates were calculated according to all these categories.

2.3.3.1. Statistical analysis. The statistical approach was performed according to the difference-in-differences method (DiD) explained by Butsic et al. (2017). This analysis allows calculating the effect of a treatment as the difference between the differences of the treated and non-treated observations before and after treatment. As stated by these same authors, it is similar to the before-after-control-impact (BACI) experimental design (Stewart-Oaten and Bence, 2001).

In the context of this work, the treatment was the zoning established by the TP Provincial law and it was evaluated individually for each one of the physiognomic groups (TF-TP, LF-TP, and OE-TP).

The analysis was conducted in R software (R Core Team, 2020) with the packages: plm (Croissant et al., 2008), sf (Pebesma, 2018), PerformanceAnalytics (Peterson et al., 2020), and ggplot2 (Wickham, 2016).

2.3.3.2. Sample units. A hexagonal grid of the study area was created with cells of 1 km^2, each cell was identified with a unique ID. Based on the vegetation map of 2001 and the TO zoning map, all the cells completely contained within the zoning and with a single natural environment cover of at least 90% were selected. From this subset, the cells on which the LUC was produced for the periods 2001–2008 and 2010–2015 were reselected. Afterwards, the transformed area for each cell for each period was recorded. The period 2008–2010 was not included in this analysis because it represents the gap between the sanction of the National Forest Law (end of 2007) and the TP Provincial law (2010).

2.3.3.3. Explanatory variables. The TP Provincial law zoning (*Corridors* and *non-Corridors*) was the effect we were interested in estimating. Three controls covariates were included: the distance to the nearest prior transformed area given that is one of the most important deforestation drivers in the region (Volante et al., 2016; Le Polain de Waroux et al., 2016), the mean precipitation (mm) according to Formosa's official isohyet map (UPCA,) for being reported as an important factor in deforestation (Kirby et al., 2006; Adámoli et al., 2011) and Formosa's territory overlaps with the Dry Chaco and Humid Chaco subregions, and the distance to the nearest road (IGN, 2021), either national or provincial, which also has been reported to be important (Kirby et al., 2006). The distance measures were calculated using ArcMap 10.3.

2.3.3.4. Model. The employed model was:

$$TA = Period * Z_{TP} + Prec_{mm} + Dist_{TA} + Dist_{Rd}$$

with:

- **TA:** transformed area of a hexagonal cell (ha).

- **Period:** Pre/Post TP Provincial law.
- **Z_TP**: Corridors / non-Corridors zone.
- **Prec_mm:** mean annual precipitation (mm)
- **Dist_TA:** distance to the nearest prior transformed area (m).
- **Dist_Rd:** distance to the nearest road (m).

The variable Period is a binary variable with a value of 1 for Post TP Provincial law (2010–2015) and 0 for Pre (2001–2008), the variable Z_TP is also binary with a value of 1 for *Corridors* zone and 0 for *non-Corridors* zone. The coefficient of the interaction is what estimates the effect of the TP Provincial law over the transformation of the natural environment.

2.3.4. *Forest fragmentation*

For a more comprehensive analysis of the forest fragmentation, the forest loss area, type of forest fragment (patch and edge), patch size, and the isolation between them were considered. The kind of forest (TF-TP and LF-TP) in which agricultural expansion occurred was analyzed for each period, classifying such expansion as perforation if a polygon of a transformed area was completely contained by a polygon of forest, or as shrinkage if the transformed area was partially contained (Fig. 3). Additionally, each drawn polygon was counted as a perforation/shrinkage event, due to the scale of mapping a single polygon can include adjacent LUCs in more than one contiguous property. The generated forest edge area was calculated considering a 100 m width buffer based on what has been reported for forests in the region (Ginzburg, 2019). Two categories were created to classify the generated edge: internal (if generated by perforation) and external (if generated by shrinkage). Based on this classification, the ratio, ha of generated forest edge to ha of forest loss type, was calculated. Differences between groups were evaluated with non-parametric pairwise Wilcoxon rank sums test (Wilcoxon, 1945). The zoning of the TP Provincial law was taken into account.

The size of the forest patches and their isolation of each year were calculated. The forest patches were classified into five size categories: less than 50,000 ha; between 50,000 ha and 100,000 ha; between 100,000 ha and 500,000 ha; between 500,000 ha and 1,000,000 ha; greater than 1,000,000 ha. The isolation was measured by the distance to the nearest neighbor with the *Proximity Analysis* tool of the ArcView 3.2 software**.** Due to the wide range of values obtained, the mean was chosen as a descriptive statistic. For both patch size and isolation analyses, the zoning by the TP Provincial law was not considered since this caused a fictitious separation that led to unreal sizes and isolations, which only added noise to the analysis. As final consideration, although the zoning established by the TP Provincial law is only applicable after the year 2010, the situation before this year was also evaluated under the zoning to check whether there were changes on the fragmentation process or not after the passing of the law.

3. Results

The overall accuracy of the LUC mapping was of 92%. Several examples of LUC visual interpretation are included in Appendix A.

3.1. *Territorial Planning Provincial Law effect on different natural environments*

The "Pearson r" correlation coefficient calculated for the explanatory variables (distances and precipitation) was $r < \pm 0.2$ in all cases. The different outcomes for the DiD model are shown in Table 2. Starting with the TP Provincial law, represented by the interaction factor Period*Z_OT (see M&M), it had a significant effect on TF-TP and OE-TP but with opposite signs. TF-TP showed a negative coefficient meaning that the *Corridors* zone reduces the transformed area for this physiognomic group. Contrary, the positive sign for OE-TP indicates the LUC increases over this assortment of natural environments within the same zone.

Regarding the control covariates, the precipitation (Prec_mm) was significant for both types of forest with a negative coefficient denoting that transformed area increases in more arid regions of the province. The distance to the nearest previous transformed area (Dist_TA) had a positive significant coefficient for TF-TP as for OE-TP. The distance to the nearest road (Dist_Rd) was only significant for LF-TP and had a negative effect.

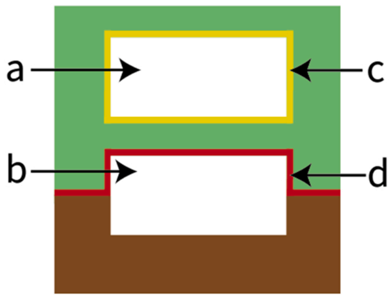

Fig. 3. Examples of perforation (a), shrinkage (b), internal edge (c) and external edge (d) are shown. The forest (green), another environment (brown), and natural environment loss (white). For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

Table 2
The Difference in Difference (DiD) model. Coefficients and statistical significance of the effect of the TP Provincial law and other factors over the transformation of natural cover land according to the physiognomic groups of the TP Provincial law. Significance: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ and Ns = $p > 0.05$. Model is described fully in Materials and Methods. The sample size was TF-TP n = 3073, LF-TP n = 359, OE-TP n = 2976.

Model	$TA = Period * Z\_TO + Prec\_mm + Dist\_TA + Dist\_Rd$		
	Tall Forest (TF- TP)	Low Forest (LF- TP)	Other natural environments (OE-TP)
Period *Z_OT	-6.61*	Ns	14.34 * **
Prec_mm	-2.76×10^{-2}***	-4.64×10^{-2}*	Ns
Dist_TA	7×10^{-4}***	Ns	4×10^{-4} *
Dist_Rd	Ns	-9×10^{-4}**	NS

3.2. *Forest and other natural environments loss*

Between 2001 and 2015 agricultural expansion caused the transformation of 537,000 ha of natural cover land in the province of Formosa. The most affected natural environment was the forest with 54.7% of total transformed area. For the three periods analyzed the forest presented the highest values of loss rate, being lower during the period 2001–2008 before the National Forest law (−0.47 yr^{-1}), higher during the 2008–2010 interval (−0.97 yr^{-1}), and intermediate in 2010–2015 after the TP Provincial law (−0.69 yr^{-1}).

In the comparison of the LUC considering the zoning established by de TP Provincial law, during 2001–2015 the *non-Corridors* zone accounted for 79% on average of agricultural expansion, nonetheless the period after the TP Provincial law held the lowest value (70%) (Fig. 4A). From the detailed distribution of LUC over the TP Provincial law categories (Fig. 4B), within the *Corridors* zone, the TF-TP concentrated the highest percentage. However, focusing on what happened pre and post the TP Provincial law, the percentage of TF-TP dropped from 78% to 53%. Furthermore, the OE-TP increased from 15% to 28%. In the *non-Corridors* zone, TF-TP presented about 45% on average of the LUC. After the sanction of the TP Provincial law, it did not show a shift as pronounced as the *Corridors* zone.

The LF-TP, on the other hand, presented a similar pattern when comparing 2001–2008 and 2010–2015 for both zones. Despite the fact that they represent a greater contribution to LUC over the *Corridors* zone, both zones showed a percentage increase.

Regarding the loss rates (Fig. 4C), the *non-Corridors* zone displayed higher values than the *Corridors* zone for all categories through all periods. Nevertheless, both zones exhibited the TF-TP as the category with the highest loss rates. In the *non-Corridors* zone, the rate of TF-TP, as well as OE-TP, manifested a sharp peak in 2008–2010. The rates of TF-TP and LF-TP seemed to increase in 2010–2015 in comparison with 2001–2008. Concerning the *Corridors* zone, the peak in 2008–2010 was also present but only for the TF-TP and LF-TP; however, the decrease of TF-TP in 2010–2015 was less pronounced.

3.3. *Forest fragmentation*

Agricultural expansion between 2001 and 2015 caused the loss of 293,472 ha of forest (which represents 8% of the existent forest in 2001) and the generation of 52,979 ha of forest edge. For the first two periods analyzed, the generated forest edge occurred mainly in the *non-Corridors* zone (≈70%) while for 2010–2015 this percentage was near 50% (Fig. 5A).

As regards the distribution of forest loss type (Fig. 5B), both zones showed a different configuration. The *non-Corridors* zone had a preponderance of shrinkages, especially for periods 2001–2008 and 2010–2015. In contrast, in the *Corridors* zone, a major percentage of forest cover loss took place in the form of perforations.

The ratio of generated edge and forest loss type manifested a common trend for both zones. Firstly, in all periods this ratio is greater for perforations than for shrinkages (Fig. 5C). Moreover, in most cases, the ratio was, at least, 2.5 times higher. Secondly, if the periods 2001–2008 and 2010–2015 are compared, the ratio of generated edge to forest loss type for both perforations and shrinkages slackened.

As regards forest patches, in 2001, 2008, and 2010, more than 92% of the forest area was in patches greater than 1 million hectares, whereas patches of up to 50,000 hectares represented less than 6% (Fig. 5D). In 2015 this distribution changed, the patches greater than 1 million hectares represented 47.3%, and the ones of up to 50,000 hectares the 12.4%. Regarding the isolation between the forest patches and how it changed as a result of agricultural expansion, the mean distance to the nearest neighbor decreased from period to period, from 523 m in 2001 to 471 m (2008), 470 m (2010), and 456 m (2015).

4. Discussion

The agricultural expansion in Formosa through the years 2001–2015 took place mainly over the forests. This stemmed in forests presenting the highest cover loss and loss rates among all the natural environments. Despite this fact, the DiD model showed that the TP Provincial law had a significant effect over TF-TP in reducing its land-cover transformation. The *non-Corridors* zone accounted for most of the LUC, while the TF-TP in the *Corridors* zone had the lowest LUC after the enactment of the law. All these results point towards Formosa's TP Provincial law being successful at promoting the conservation of forests.

In terms of forest fragmentation, the *Corridors* zone showed a greater proportion of the generated forest edge as the product of agricultural expansion. However, both zones presented a different distribution of perforations and shrinkages. A general tendency to a

Period	2001 - 2008	2008 - 2010	2010 - 2015
Transfmored area (10^3 ha)	211.27	131.06	195.32

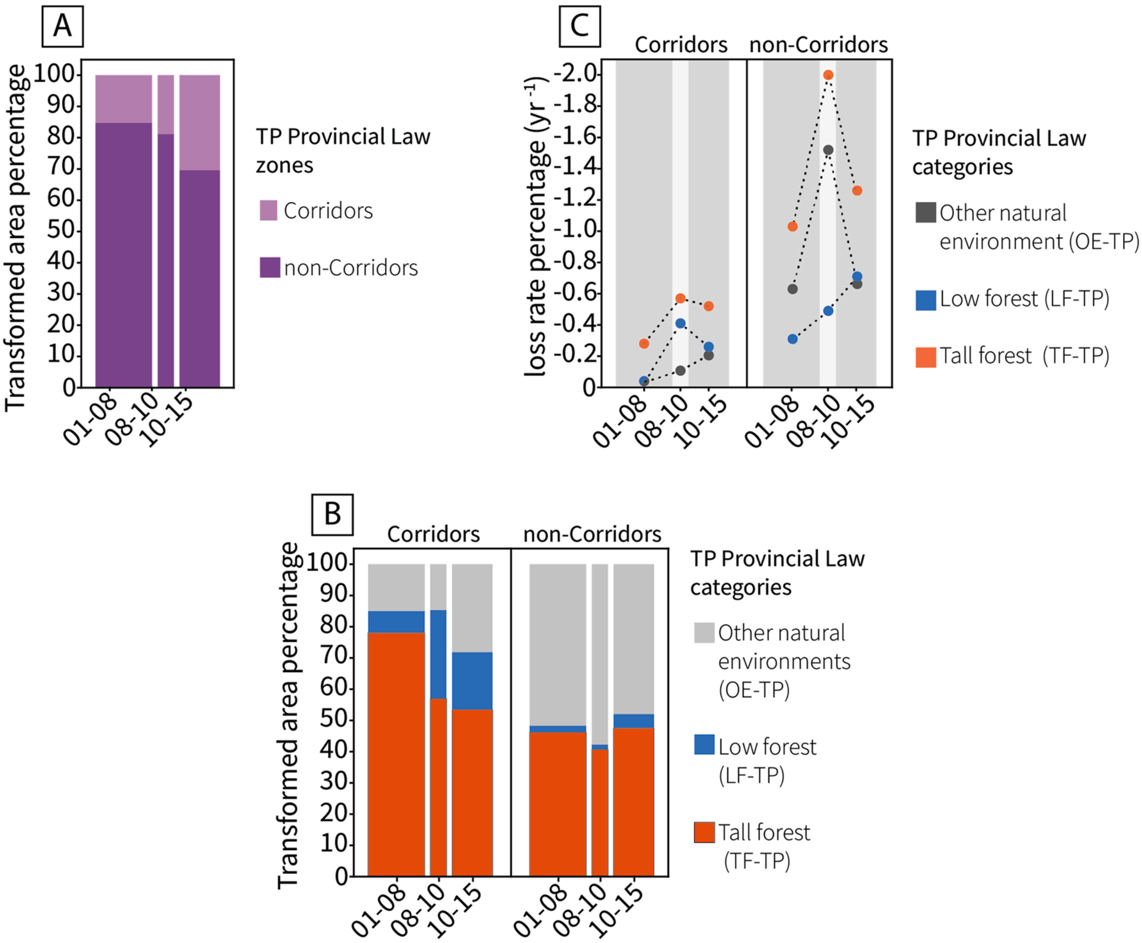

Fig. 4. A. The Percentage distribution of total LUC between 2001 and 2015 according to the TP Provincial zones: Corridors (light violet) and non-Corridors (dark violet), divided into three periods: 2001–2008, 2008–2010, and 2010–2015. B. The Percentage distribution of total LUC between 2001 and 2015 according to the TP Provincial law categories: tall forest (TF-TP) (orange), low forest (LF-TP) (blue) and other natural environments (OE-TP) (gray) of the province of Formosa, divided into Corridors and non-Corridors zones, and into three periods: 2001–2008, 2008–2010, and 2010–2015. C. Forest loss rates for the whole province of Formosa between 2001 and 2015 according to the TP Provincial law categories: tall forest (TF-TO) (orange), low forest (LF-TO) (blue) and other natural environments (OE-TP) (dark gray), divided into Corridors and non-Corridors zones, and into three periods: 2001–2008, 2008–2010, and 2010–2015. For letters A-C, the bar width is proportional to the length of each period to make visually explicit the difference in duration. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

smaller ratio of generated edge area to forest loss was observed. Lastly, the fragmentation process produced an augment in the number of patches and a reduction in their sizes and segregation.

4.1. Forest cover transformation

During agricultural expansion in Formosa between 2001 and 2015, the forest was the most transformed natural environment presenting the highest cover loss (i.e. absolute number of hectares) and loss rates (i.e. magnitude and speed of cover change). This greater transformation of forest cover in comparison to other environments can be explained mainly by the fact that the forest is settled on the most fertile soils of the province, making it more attractive for new agricultural projects even if the cost of its transformation is higher (Adámoli J., personal communication). Thus, new livestock farms with pasture implantation are made in these environments even though the crop requirements are widely exceeded.

Period	2001 - 2008	2008 - 2010	2010 - 2015
Generated forest edge (10^3 ha)	27.01	10.65	15.32

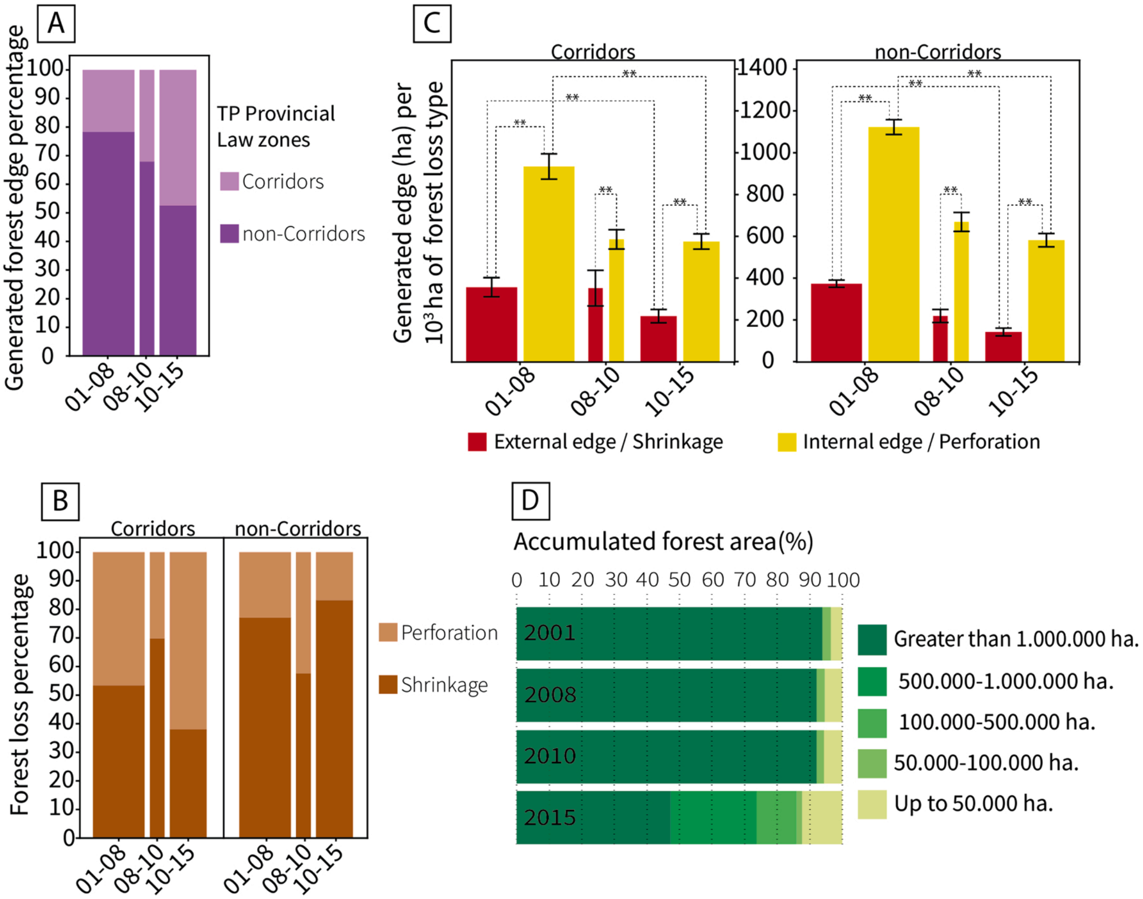

Fig. 5. A. The percentage distribution of total generated forest edge due to LUC between 2001 and 2015 according to the TP Provincial zones: Corridors (light violet) and non-Corridors (dark violet), divided into three periods: 2001–2008, 2008–2010, and 2010–2015. B. The percentage distribution of forest loss due to total LUC between 2001 and 2015 in the province of Formosa, divided into Corridors and non-Corridors zones, and into three periods: 2001–2008, 2008–2010, and 2010–2015. The forest loss is classified into shrinkage (dark brown) and perforation (light brown). C. Ha of generated forest edge per 10^3 ha of forest loss type due to LUC between 2001 and 2015 in the province of Formosa, divided into Corridors and non-Corridors zones, and into three periods: 2001–2008, 2008–2010, and 2010–2015. The forest loss is classified into shrinkage and perforation. The generated edge is classified into external (by shrinkage) (red) and internal (by perforation) (yellow). See materials and methods. **$p < 0.01$, pairwise Wilcoxon rank sum tests. D. Formosa's forest patch size distribution is shown as percentual accumulated forest area for the years 2001, 2008, 2010, and 2015. For letters A-C, the bar width is proportional to the length of each period to make visually explicit the difference in duration. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

Regarding loss rate, Formosa's forest showed the highest value for the period 2008–2010 (Section 3.2), corresponding to the intervening years between the National Forest law and the TP Provincial law. This peak of pressure on the resource to be protected before the enactment of a law that regulates land clearing was also observed in other provinces of the Chaco region (Adámoli et al., 2011). For example, −3.15 in Santiago del Estero, −1.34 in Salta and −0.73 in Chaco (UMSEF, 2012). The same source cites a rate of −1.03 for Formosa, similar to the loss rate of −0.97 obtained in this study. This opposite effect to the one sought could occur because foreseeing the law would determine the total prohibition of land clearing, many producers would rush to carry out their approved LUC projects for fear the measure would be retroactive and could affect them too. Moreover, many other producers could have done their LUC without having authorization, feeling they were not going to be able to perform any type of land clearing in the future.

4.2. Territorial Planning Provincial Law effect on different natural environments

The objective of the DiD model was to estimate if the TP Provincial law zoning affected the transformation over the physiognomic groups established by said law. As showed in Section 3.1, the TP Provincial law affected TF-TP and OE-TP. Over TF-TP, the law decreases the LUC, while over the OE-TP it increases it. In addition to this, the model allowed to account for the effects of covariates which are not affected by the enactment of the TP Provincial law but have been reported to affect agricultural expansion, e.g. the mean annual precipitation, distance to the previous transformed area, and distance to the road. The negative correlation of mean annual precipitation with the transformed area for both types of forests could be interpreted as a major presence of LUC over drier regions, this is consistent with the fact that the predominant crops in the province are exotic pastures for cattle, such as Gaton Panic or Buffel Grass, which can bear a low water regime (Adámoli et al., 2011; Grau et al., 2005; Volante et al., 2015). Furthermore, there is poor forest availability for this activity in the humid region of the province in which most of the terrain gets flooded. On the other side, the positive relationship of the distance to the previous transformed area of the TF-TP and OE-TP would indicate that transformations are not being as contagious as it has been reported for other zones of the Chaco region (Volante et al., 2016) or the world (Boakes et al., 2010; Robalino et al., 2012). The reason for this outcome could be the relatively low percentage of LUC in the province and the fact that most of agricultural expansion has been done by medium-large producers where possibly the acquisition of the land is greatly associated with land prices (Le Polain de Waroux et al., 2016). Both factors could tilt the balance to a less concentrated distribution of LUC. Nonetheless, this does not imply a static influence of neighboring land clearings, Formosa could be experiencing an incipient transformation process and it is sowing future contagious events. Lastly, the distance to the road was only significant for the LF-TP; however, just a small percentage of total agricultural expansion occurred over this physiognomic group.

4.3. Territorial Planning Provincial law categories and zoning

The *non-Corridors* zone held most of agricultural expansion in all periods; however, after the enactment of the TP Provincial law it registered its lowest value. In this regard, this decrease and the corresponding highest value of the fraction of LUC within the *Corridors* zone could be the result of a mere growth of agricultural expansion overall Formosa. The existent LUC by the year 2015 represented only 10% of the territory, which leaves plenty of room for future LUC taking into account the total percentage that the law would permit considering the physiognomic groups and the zoning (≈32% of the province's territory).

From the analysis of forests under the TP Provincial law classification, ignoring the zoning, a far greater transformation of the TF-TP with respect to the LF-TP was observed. This can be explained by two reasons; firstly, again, the general trend is to carry out LUC on the best soils. In this way, TF-TP is preferred although the soils on which LF-TP is settled fulfill the necessary requirements for pastures. Secondly, a larger area of TF-TP occurs in the province in contrast with the one of LF-TP (Fig. 1C).

Notwithstanding the forest was the most affected natural environment by agricultural expansion, the TP Provincial law (enacted in 2010) appears to have been effective in protecting TF-TP by zoning and restricting the LUC across the province. In line with the previous results of the DiD model, the TF-TP exhibited the lowest percentage of LUC within the *Corridors* zone after the enactment of the law. Furthermore, the OE-TP of the same zone reflected an increased percentage of LUC which was also compatible with the DiD model. Conversely, the LF-TP presented a similar temporal transformation change in both zones. Once more, this outcome is in line with the results of the DiD model, where the law did not affect LF-TP, insofar as this statistical model is based on the differences between periods between zones.

As stated before, the loss rate gives an idea of the change magnitude and speed. The higher rates in the *non-Corridors* zone of a given period indicated that the amount of LUC was considerably greater in comparison with the *Corridors* zone. The same applies to the higher rate for TF-TP in comparison with the other categories. After the enactment of the TP Provincial law, both zones had their rates increased compared with 2001–2008. In the beginning, this could seem contradictory but the law only specifies percentage restrictions of the total area to be transformed, there is no mention about the speed of the process. Considering Formosa's agricultural expansion has started relatively recently, and the location of the province within one of the largest global deforestation hotspots, loss rates are expected to have increased.

Despite the fact the TF-TP in the *Corridors* zone was the only kind of forest that registered a LUC reduction, the results are positive at the regional scale. To begin with, the TF-TP is the more abundant forest in the province and where most of agricultural expansion has occurred; therefore a reduction of its transformation would show a positive shift in its conservation. Moreover, even when LF-TP contribution to the total transformed area incremented, the major part of its extension is under the *Corridors* zone under which the allowed transformation percentage is lower. This means that, in the long run, the final LF-TP transformed area should be less than in the absence of zoning.

Notwithstanding the specificity of the zoning programs, other studies have also reported positive results about curtailing deforestation using this kind of policy. In Cameroon, Central Africa, the classification of forest areas and the designation of forest production units through land-use zoning effectively controlled deforestation (Bruggeman et al., 2015). In Bhutan, South Asia, forest production units were also implemented and reduced half of the forest loss that would have taken place without these units (Bruggeman et al., 2018). The abovementioned studies also assessed the presence of deforestation caused by the leakage effect (i.e. the displacement of land uses to the periphery of areas with restricted uses (Lambin and Meyfroidt, 2011)), as many other studies have mentioned it is an important factor to consider when analyzing the outcomes of natural resources policies (Dou et al., 2018; Heilmayr et al., 2020; Meyfroidt and Lambin, 2009; Moffette and Gibbs, 2018). TP Provincial law, at least at the province scale, could have, in some way, avoided this effect since land-use regulations include all natural environments and the full extent of its territory, so that land clearings by leakage, as a response to forest land-use limitations, could be legally contained by the restrictions on the OE-TP category. Piquer-Rodríguez et al. (2018a), concluded, after evaluating the impact of economic policies on future land-use conversions in Argentina, that area-based policies such as zoning appear to be a more straightforward tool for avoiding unwanted environmental impacts in the Chaco, if properly enforced.

In Formosa, only 1.6% of deforestation occurred over National Forest Law forbidden areas (UMSEF, 2020), which is a positive result according to the law's aim of protecting the native forest at a national scale if compared to other provinces such as Santiago del Estero and Chaco, with 74% and 60% respectively (Camba Sans et al., 2018; UMSEF, 2020). However, Vallejos et al. (2021) when evaluating illegal deforestation at the plot scale, between 2008 and 2017 in the Dry Chaco, they detected that in this portion of Formosa at least 4% of deforestation over permitted areas occurred beyond the plot limits established by Formosa's TP Provincial law (*Corridors* zone up to 20% of the property; *non-Corridors* zone up to 60%). These results are not necessarily contradictory, as they originate from an analysis at a different scale. It would be interesting, for future studies, to have a complete and updated cadastral map of Formosa that allows an assessment of the outcomes of the TP Provincial law at a plot scale, similar to Vallejos et al. (2021), and to evaluate whether such discrepancies arise in order to better understand the situation in Formosa and enrich the discussion about land-use zoning policies.

4.4. Forest loss type and fragmentation

Agricultural expansion caused forest cover loss and the generation of new forest edge. During the first two periods, most of the edge generation occurred in the *non-Corridors* zone as well as most of the LUC. However, during 2010–2015 the percentage distribution of the generated edge was almost 50/50 between zones even though the LUC distribution remained being primarily over the *non-Corridors* zone. This situation is understandable when the forest loss type distribution is considered. Both zones presented a different configuration; the *Corridors* zone had a higher presence of perforations while the *non-Corridors* zone was predominated by shrinkages. By definition, a perforation generates more edge than a shrinkage (see M&M, Fig. 3), so the higher amount of LUC observed in the *Corridors* zone compared to previous periods and the predominance of perforations explain the shift of the generated edge towards a more even distribution. This can be seen as an undesirable side-effect on forest conservation, since the creation of forest edge disturbs the biotic and abiotic conditions and could ultimately lead to a continuous process of edge development (Harper et al., 2005) in addition to the hunting, selective logging, and increasing fire frequency and intensity that have been reported to be associated with forest edges (Barlow et al., 2016; Cochrane, 2001; Cochrane and Laurance, 2002; Ewers et al., 2006). The reason for this undesired outcome could be that the TP Provincial law, even though restricting the amount of area to be transformed, did not include any guidelines for its spatial configuration. It would be beneficial to incorporate considerations in this regard in the TP Provincial law implementation.

The overall trend to a smaller ratio of generated edge area to forest loss area indicates larger average size LUC events, both for perforations and shrinkages. This increase in the LUC size has, in general, been seen in the entire region (Gasparri and Grau, 2009) given that the main actors present in recent years have been medium and large agribusiness (Adámoli et al., 2011).

Regarding forest fragmentation, between 2001 and 2015 this process produced an increase in the number of patches, a decrease in their sizes, and less isolation between them, showing a behavior similar to the one outlined by Fahrig (2003). This was because agricultural expansion was mainly affecting the larger patches, subdividing them into smaller ones. In addition to this, if the remaining forest area (92% of the existing forest in 2001) is considered, the results here obtained could indicate an early stage of the fragmentation process. In support of these results, while Formosa's 2015 forest patch size distribution holds 86% of the forest land cover under patches greater than 1,000,000 ha, the world's subtropical dry forest percentage reported by FAO (2020) for the same year and the same size category is about 56%.

Gasparri and Grau (2009) exposed that, within the ecoregion scale, Argentine Dry Chaco forest fragmentation may be comparatively less important than habitat transformation, but represents an additional problem to take into account. Torrella et al. (2018) simulated future scenarios for Formosa under different forms of landscape planning regarding the policies of the TP Provincial law. They considered both the existence and absence of zoning (*Corridors* and *non-Corridors*) combined with a high/low deforestation rate and the inclusion of spatial planning to minimize forest fragmentation. The results obtained showed a less forest fragmentation occurred under a high forest loss rate, the presence of zoning, the differential maximum percentage of admissible LUC, and the contemplation of a spatial configuration design, compared to the scenarios without the zoning. This pattern is consistent with the results herein presented and suggests the possible long-term benefits of this kind of policy and the importance of considering spatial planning guidelines.

Formosa was the only province that implemented the conservation corridors proposal made by National Parks Administration. The *Corridors* zone comprises half of the province's territory, more than 3.5 million hectares, representing almost 6% of the total area of the Argentine Chaco region. Taking into account the aforementioned results on the positive effects on TF-OT in the *Corridors* zone and the study by Piquer-Rodríguez et al. (2015), in which the effect of land conversion on forest connectivity for the entire Argentine Chaco was analyzed and was found that in absence of coordination and consistency in conservation planning and landscape design even zoning policies can erode forest connectivity at ecoregion scales, it would be important for other provinces to incorporate the regional strategy of corridors conservation, contemplating not only the forest but all types of natural environments. Achieving the implementation of operative conservation corridors on a larger scale is an issue of global importance (Beita et al., 2021; Brodie et al., 2016; Lombard et al., 2010).

Last but not least, agricultural expansion and the forests loss and fragmentation process here analyzed could involve a threat to biodiversity conservation. It has been reported to affect the structure, composition, and recruitment of the plant community (Cagnolo et al., 2006; Ginzburg, 2019; López de Casenave et al., 1995; Torrella et al., 2015), as well as the associated fauna (Camino et al., 2020; López De Casenave et al., 1998; Núnez-Regueiro et al., 2015).

4.5. Satellite remote sensing tool

The use of satellite remote sensing tools proved to be a practical and convenient way to tackle this kind of study, as already has been mentioned in the literature (Roughgarden, 1991). The Landsat program is the oldest earth-observing satellite system and remains one of the most important sources of information. Still, in order to carry a more detailed study of a particular zone, incorporating other technologies such as hyper spectral, SAR, and LIDAR sensors since they offer a narrower bandwidth, information on the vertical structure of vegetation, and 3D high-resolution mapping would be interesting for a more comprehensive analysis of the impact of the TP Provincial law on forest conservation. In locations like the Chaco region, SAR imagery becomes more relevant as the wet season hinders the image acquisition by optical satellites.

5. Conclusions

This study assessed the outcomes of Formosa's first Territorial Planning Provincial law over the forest loss and fragmentation process. The TP Provincial law seems to have accomplished its objective of promoting forest conservation, at a regional scale, given that the priority conservation area (*Corridors zone*) showed lower participation of the TF-OT in the LUC distribution after its enactment. However, the *Corridors zone* also had a greater contribution to the total forest edge generated, which undermines forest conservation. This did not mean that the result was no longer positive, as forest loss were reported to be more serious in terms of forest conservation (Gasparri and Grau, 2009), but it exhibited the importance and the need to include spatial configurations guidelines for future LUC, as claimed by Torrella et al. (2018). It would be interesting to continue monitoring the dynamics of forest loss and fragmentation under the TP Provincial law to assess the long-term effects.

Land-use zoning programs have been shown to have mixed results in halting deforestation (Jusys, 2018; Nelson and Chomitz, 2011). Identifying policies that shepherd agricultural land-use change into a reduced pressure on forests and assessing their relative impact on agricultural expansion is essential (Meyfroidt et al., 2014). The strategy proposed by Formosa's TP Provincial law of considering all the existing natural physiognomies throughout the province's territory, rather than just protecting the forests over which most of agricultural expansion has occurred (Graesser et al., 2015), seems to have reached this goal. This result, in addition to Formosa's location within one of the most important deforestation hotspots in Latin America and the world, and the development of its recent agricultural expansion under the context of land-use law, could position Formosa as an example of the relevance of early planning/legislation on the use of natural resources. This zoning strategy could encourage future productive scenarios that include broader nature conservation by guaranteeing the existence of the different ecosystems of a region. Likewise, the land-use regulation over the full diversity of natural environments could mitigate the impact of common situations in developing countries which hinder the management and conservation of natural resources, such as land ownership, poverty, and population growth (Heltberg, 2002; Mengesha and Ayano, 2021; Schultz, 2003). All things considered, it is worth mentioning that although policies are useful, the collaboration of state institutions, conservation organizations, and original inhabitants is crucial for long-term conservation (Camino and Arriaga Velasco-Aceves, 2021).

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2021.e01846.

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