Parcel-Level Deforestation Hazard Rates in the Paraguayan Chaco: A Multi-Scale Empirical Analysis of Annual Clearing Dynamics on Large Cattle Ranches

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Abstract

Cattle ranch expansion across the Paraguayan Chaco generates parcel-level clearing rates that appear inconsistent with regional deforestation statistics, raising concerns that REDD+ baselines constructed from proxy parcels overstate forest loss (a baseline over-crediting debate that turns on denominator consistency between parcel hazard and regional flows). Because parcels undergoing active conversion are cleared within compressed development windows of one to five years, their annualised hazard rates necessarily exceed long-run regional averages that dilute clearing across the full estate of active and inactive properties. This paper develops a deterministic scaling identity that resolves the apparent inconsistency by formally linking parcel-scale hazard intensity to regional clearing magnitudes through the legally convertible forest fraction (g) and the share of parcels actively clearing in any given year (f). From 22 cadastral parcels across nine ranch sites in the Western Region (excluding the northern UNESCO Biosphere Reserve), annualised clearing rates derived under the Verra BL-PL module (VMD0006) from Landsat imagery over 2012 to 2020 yield a sample mean of 14.99% of total parcel area per year (not percent of regional forest; 95% bootstrap CI: 9.86 to 20.68; N = 22). The distribution is right-skewed (skewness = 1.05) with substantial heterogeneity (SD = 13.15; range 0.15 to 49.67). Discrete-time hazard analysis confirms front-loaded clearing: mean hazard in Year 1 is 0.28,

declining to 0.05 by Year 3 (paired t = 3.04, p = 0.006). Inverse application of the identity recovers a median implied activity share $f \approx 0.12$ (95% SI ≈ 0.07–0.19), aligned with a directly measured nine-year mean $f \approx 0.121$ on an expanded 46-parcel set and with the committed-conversion mean of 15.78%/yr under a $D\% \geq 20$ filter. A secondary forward uncertainty exercise (sampling f from the scenario band) yields mean implied deforestation of order 238,000 ha/yr (58.4% of draws in the 160,000–300,000 ha/yr historical band) and is reported as prior-sensitive, not as independent confirmation. Regional clearing rates, forest-stock inputs used in scaling, and any imputed parcel Forest% are estimates that would benefit from more detailed primary analysis. The present parcel-level work uses Chaco Vivo–linked parcels and related project documentation; it does not claim a nationally representative or wall-to-wall sample of the Paraguayan Chaco. The proxy sample is small ($n = 22$) and non-random. In the primary $N = 22$ scaling exercises f is identified as a residual; on the expanded 46-parcel universe a year-wise activity fraction is measured directly (mean 0.121) and used as a consistency check, not as a wall-to-wall regional census. Larger, more detailed sampling and tightened forest-cover measurements are reserved for a planned expansion study.

The 14.99%/yr figure is not re-estimated in this paper; it is the validated output of the VMD0006 BL-PL module as applied in the Chaco Vivo Project Description under VCS Standard v4.7. This paper takes that module-derived rate as given and asks whether it can be reconciled with independently observed multi-decadal clearing records across the Paraguayan Chaco.

An independent expanded-sample validation comprising 24 additional cadastral parcels drawn from fifteen separate landholders corroborates the central estimate: committed-conversion parcels from the combined 46-parcel universe yield a mean rate of 15.78%/yr [11.13, 21.03], and the directly measured nine-year activity fraction of 0.121 falls at the centre of the scaling identity's implied range. Parcel-level Forest% for the twenty-four expanded cadastral parcels is not in the proxy archive (centroids only). Those values are temporarily imputed and flagged as estimates: one parcel from an original-sample landholder mean where the centroid owner matches an original ranch, and twenty-three parcels from the original $N =$

22 pool mean of 75.35% (observed range 42.39–99.16%). They are not measured 2012 forest cover; any Exp forest-dependent result is sensitivity-only until GIS Forest% is supplied in the planned expansion study.

Keywords: Paraguayan Chaco; deforestation hazard rate; parcel-level analysis; BL-PL methodology; planned deforestation; cattle ranching; REDD+; proxy analysis; survival analysis; Monte Carlo simulation

1. Introduction

The Paraguayan Chaco has experienced sustained deforestation driven primarily by frontier cattle ranch expansion under the regulatory framework established by Paraguayan Forestry Law (Law 422/73) and land-use planning administered by MADES (Ministerio del Ambiente y Desarrollo Sostenible).[1] Regional deforestation rates are typically reported as annual hectares cleared or as percentages of total regional area.[2] In contrast, parcel-level deforestation behaviour is governed by legally authorised land-use plans that define reserve areas and convertible forest fractions at the cadastral scale.[3]

Under the Verified Carbon Standard module VMD0006, estimation of planned deforestation for REDD+ projects requires use of proxy parcels when verifiable land-use plans are unavailable. This module expresses planned deforestation as a proportion of total parcel area (the BL-PL rate denominator confirmed in VMD0006 v1.4), not solely convertible forest area. As a result, parcel-level hazard rates derived under BL-PL logic represent clearing intensity during active development phases and are not directly comparable to regional rates without explicit scaling.

Chaco Vivo applied the BL-PL framework to a set of 22 proxy parcels selected in accordance with VMD0006 proximity and comparability

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[1] Paraguay, Ley No. 422/73 (Ley Forestal), FAOLEX https://www.fao.org/faolex/results/details/en/c/LEX-FAOC023975/.

[2] INFONA, *Nuestros Bosques: Reporte Nacional de Cobertura Forestal 2020-2022* (Instituto Forestal Nacional, Paraguay 2022) https://visor.infona.gov.py/.

[3] Paraguay, MADES, *Modified Technical Annex on REDD+* (2018) https://unfccc.int/sites/default/files/resource/Modified%20Technical%20Annex%20on%20REDD%2B_Anexo%20Tecnico_Py_030619.pdf.

requirements.[4] The resulting mean annual parcel-level deforestation hazard rate was 14.99% of total parcel area per year. This value exceeds multi-year regional averages expressed at the regional scale. However, parcel-level hazard and regional deforestation rate describe different denominators and different aggregation processes.[5]

This study reconciles parcel-level hazard rates with regional deforestation rates across the Paraguayan Chaco using an explicit aggregation identity grounded in parcel geometry and legally convertible forest fractions. The analysis has two objectives: (1) to establish that the parcel-level hazard rate derived from proxy parcels accords with observed regional deforestation magnitudes when calculated on a legally comparable basis, and (2) to show that the use of remote sensing, proxy parcels, and regional assumptions required under BL-PL need not imply exaggerated regional risk once convertible fraction and activity mixing are treated explicitly.

The result is a formal reconciliation between parcel-scale clearing intensity and regional deforestation dynamics under Paraguayan land-use law.

2. Study Area and Legal Context

2.1 The Paraguayan Chaco

The Western Region encompasses approximately 246,000 square kilometres and roughly 60% of the national territory.[6] The region is characterised by semi-arid to sub-humid dry forest ecosystems. The Gran Chaco constitutes the largest dry forest biome in South America, spanning approximately 1.1 million square kilometres across Argentina, Paraguay, and Bolivia.[7]

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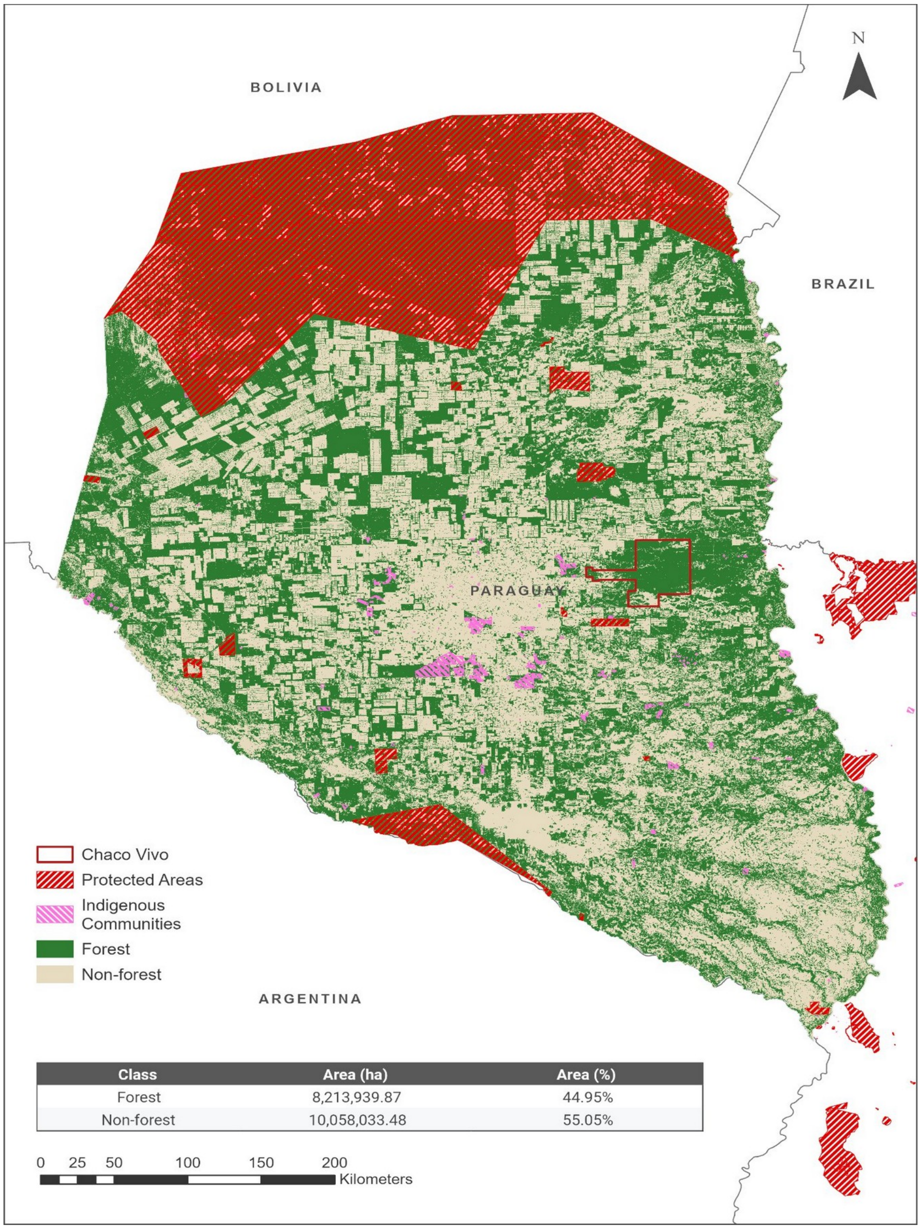
[4] Chaco Vivo Project Description (PD), Section 3: Project Area, Land Cover Analysis 2012 (on file with project proponent).

[5] Verra, *Verified Carbon Standard (VCS) Standard*, v4.7 (2024).

[6] Government of Paraguay, *Actualización del Nivel de Referencia de Emisiones Forestales (NREF) para Paraguay* (2022).

[7] Iriondo MH, 'Geomorphology and Late Quaternary of the Chaco (South America)' (1993) 7 Geomorphology 289 https://doi.org/10.1016/0169-555X(93)90059-B.



Class	Area (ha)	Area (%)
Forest	8,213,939.87	44.95%
Non-forest	10,058,033.48	55.05%

Figure 1. *Forest and non-forest land cover across the Paraguayan Chaco, with protected areas (including the UNESCO El Chaco Biosphere Reserve), indigenous community territories, and urban zones excluded. These non-eligible zones, totalling approximately 6.3 million hectares, fall outside the Law 422/73 production forest regime (see Section 2.4). Within the remaining eligible zone, forest cover is 8,213,940 ha (44.95%) and non-forest is 10,058,033 ha (55.05%). The Chaco Vivo property area is located in the central Chaco within the active agricultural conversion zone governed by Law 422/73. All proxy parcels and the project area lie south of the northern protected area boundary. Data sources: Esri and internal shapefiles from Chaco Vivo.*

Figure 1 delineates the geographic scope of this study. The northern portion of the Paraguayan Chaco, delineated by the red-hatched overlay, falls under the UNESCO El Chaco Biosphere Reserve and associated protected area designations governed by Law 352/94 (SINASIP).[8] This study excludes that zone because the legal framework governing land-use conversion there differs from the agricultural planning regime under Law 422/73 that applies to the central and southern Chaco. The remaining area, where forest and non-forest are intermixed in a patchwork of cleared ranch land and standing dry forest, constitutes the study domain. The Chaco Vivo property sits within this conversion zone at approximately 22 degrees S, 59 degrees W. Indigenous community territories, shown in pink hatching, are also excluded from the convertible forest estate. The forest/non-forest ratio in the eligible zone (roughly 45:55) is the product of four decades of cumulative conversion since the acceleration of frontier ranching in the 1980s.[9]

Deforestation is concentrated on privately held cattle ranches, typically exceeding 5,000 hectares.[10] The clearing pattern is spatially clustered along expanding road networks.[11] Cumulative forest loss more than doubled between the periods 1987 to 2000 (approximately 14,000 km^2) and 2001 to 2012 (approximately 29,000 km^2), partly due to leakage from the Eastern Region’s zero-deforestation law.[12] Between 2012 and 2017, the IUCN reported clearing at more than 200,000 hectares per year.[13]

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[8] Paraguay, Ley No. 352/94 (De Áreas Silvestres Protegidas), which establishes the Sistema Nacional de Áreas Silvestres Protegidas del Paraguay (SINASIP). FAOLEX https://www.fao.org/faolex/results/details/en/c/LEX-FAOC004659/.

[9] Baumann M and others, ‘Deforestation and Cattle Expansion in the Paraguayan Chaco 1987-2012’ (2017) 17 Regional Environmental Change 1179 https://doi.org/10.1007/s10113-017-1109-5.

[10] Perez Benitez N and others, ‘Beef-Cattle Ranching in the Paraguayan Chaco: Typological Approach to a Livestock Frontier’ (2022) 25 Environment, Development and Sustainability 3263 https://doi.org/10.1007/s10668-022-02261-2.

[11] le Polain de Waroux Y and others, ‘Land-Use Policies and Corporate Investments in the Gran Chaco’ (2016) 113(15) PNAS 4021 https://doi.org/10.1073/pnas.1602646113.

[12] Baumann M and others, ‘Deforestation and Cattle Expansion in the Paraguayan Chaco 1987-2012’ (2017) 17 Regional Environmental Change 1179 https://doi.org/10.1007/s10113-017-1109-5.

[13] IUCN NL, ‘Tackling Uncontrolled Deforestation in Paraguay’ (2020) https://www.iucn.nl/en/story/tackling-uncontrolled-deforestation-in-paraguay/.

The geographic scope covers the central and southern Chaco, where operations subject to Law 422/73 are concentrated. The analysis excludes the northern El Chaco UNESCO Biosphere Reserve.[14]

2.2 Legal Framework for Land-Use Conversion

Land-use conversion is governed by Law 422/73 (Ley Forestal) and Decree 18831/86, administered by MADES. Forest conversion requires an approved Plan de Uso de la Tierra at the full cadastral property scale. Ley 422/73 Art. 42 requires that rural properties exceeding 20 hectares in forest zones maintain a minimum of 25% of natural forest area as a legal reserve (or else reforest 5% of the property); Decreto 18831/86 Art. 11 restates the 25% rule. The 1986 baseline commonly applied in practice (forest present as of the decree date / later SEAM practice, summarised *e.g.* in USAID/TGCC) is not stated in Art. 42 wording alone. Additional protection strips of 15% between agricultural plots and riparian buffers of 5% where watercourses are present further reduce the convertible fraction, so that the effective non-convertible share typically exceeds the 25% statutory minimum. MADES assesses compliance relative to total property area, meaning any parcel-level analysis must use total parcel area as its denominator.

2.3 The Chaco Vivo Property as a Reference Case

The Chaco Vivo property comprises 187,916 hectares, with 108,077.4 hectares designated as legally convertible ($g = 0.575$).[15] This value is consistent with the layered reserve requirements under Law 422/73: the 25% statutory reserve, combined with protection strips and riparian buffers, leaves approximately 57.5% of the property eligible for conversion. Regional statistics yield g values as low as 0.40 for properties with extensive watercourse buffers; newly acquired frontier ranches with minimal riparian constraints exhibit g values from 0.55 to 0.90.[16]

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[14] UNESCO MAB (n 1).

[15] Chaco Vivo PD (n 10) s 3: $g = 108{,}077.4 / 187{,}916 = 0.575$.

[16] Expert opinion letter from forest engineer with decades of Chaco experience including INFONA work (on file with project proponent).

2.4 Convertible Forest Estate

The scaling identity developed in Section 3.4 requires an estimate of A_{conv}, the total legally convertible forest area across the study domain. No single published source reports this figure directly, because it depends on the intersection of forest-cover data, protected-area boundaries, indigenous territory designations, and the property-level reserve requirements of Law 422/73. The estimate is therefore assembled from multiple publicly available data streams and involves assumptions at each stage. This section sets out the derivation, identifies the assumptions, and evaluates the margin within which the estimate is likely to fall.

Three quantities are assembled. First, total remaining forest cover in the Western Region is estimated from published national forest statistics (Step 1). Second, forest within zones governed by legal frameworks other than Law 422/73 is estimated and reported as a parallel eligible-zone cross-check (Step 2 / Figure 1), not as an intermediate minuend in the central A_{conv} multiply. Third, an aggregate effective-reserve factor under Law 422/73 is applied to the Step 1 regional forest total to obtain the central convertible estate used in the scaling scenarios.

Step 1: Western Region forest cover (circa 2022). INFONA's national forest monitoring programme reports total national forest cover of 17,727,757 hectares as of the 2020–2022 reporting period, representing 44.3% of national territory. The Western Region accounts for the large majority of this national total. USAID/TGCC independently reported private Chaco forest (excluding indigenous and protected areas) declining from 15,655,235 hectares forested in 2000 to 12,355,612 hectares remaining in 2014, a table-total loss of 3,299,624 hectares over 2001–2014 (average 235,687 ha/yr). Adjusting for subsequent clearing using INFONA's multi-year window reporting for 2015–2022, which documents annual deforestation in the range of 160,000 to 330,000 hectares per year, yields a 2022 Western Region forest estimate in the vicinity of 10.8 million hectares. INFONA's Nuestros Bosques 2020–2022 report (Cuadro 27) independently records Occidental native-forest land-use change of 4,740,959.7 hectares over 2005–2022 (annual mean approximately 278,880 ha/yr over those 17 years as stated in the report). The same Cuadro's 2015–2022 windows sum to approximately 1,520,139 hectares, aligning closely with the −1,528,000 hectare plug used above (a small difference attributable to rounding and window aggregation). As a longer-horizon peer cross-check (not an INFONA product), MapBiomas Paraguay reports 8.19 Mha of woody vegetation ("Vegetación Leñosa") loss over 1985–2022. These records are consistent with the same order of magnitude as the USAID/TGCC path carried forward from a 2014 endpoint, without relying on any single unverified cumulative triad.

Step 2: Subtraction of non-eligible zones. The eligible study area comprises only those lands subject to Law 422/73's production forest regime. All areas governed by other legal frameworks are excluded from the forest classification. Three categories fall outside this regime: protected areas designated under SINASIP (Law 352/94), indigenous community territories administered under distinct tenure arrangements, and urban zones. The combined excluded area totals approximately 6.3 million hectares, leaving an eligible zone of roughly 18.3 million hectares within the Western Region's 24.6 million hectare total (Figure 1). Because no single consolidated spatial dataset reports this figure precisely, the 6.3 million hectare exclusion is itself an estimate derived from the available protected-area boundaries, indigenous territory designations, and urban footprints in publicly accessible GIS datasets (Esri, FAO, NOAA, USGS, OpenStreetMap).

The largest single exclusion is the UNESCO El Chaco Biosphere Reserve (designated 2005), which occupies the northern Western Region and extends across more than four million hectares; its six core protected areas alone account for approximately 1.7 million hectares (including Defensores del Chaco and Médanos del Chaco National Parks). Forest within these designations is governed by Law 352/94 (SINASIP), not the agricultural land-use planning regime under Law 422/73. (A fuller protected-area inventory is reserved for supplementary material.)

Indigenous community territories constitute the second excluded category. Available reports indicate that titled indigenous holdings in the Western Region amount to at least 500,000 hectares, with additional untitled claims; these lands are administered under distinct tenure arrangements outside

Law 422/73. (Detailed tenure inventory reserved for supplementary material.)

Not all of the excluded area is forested. The Figure 1 spatial analysis classifies the remaining eligible zone as containing 8,213,940 hectares of forest (44.95%) and 10,058,033 hectares of non-forest (55.05%). This eligible-zone forest figure is the Step 2 / Ref. sensitivity basis in Table 1, not the central A_{conv} multiply.

Because the Figure 1 classification was produced for the Chaco Vivo project area analysis and may reflect a different reference date or classification methodology than the INFONA national reporting, the two figures should not be expected to align precisely. These differences arise from the routine variation between remote-sensing classification systems and national forest inventory methodologies, compounded by differences in reference dates and spatial boundary definitions. For the purpose of the A_{conv} derivation, the regional forest estimate (approximately 10.8 million hectares) is adopted as the starting point. This figure is assembled from USAID/TGCC private-Chaco inventory covering 14 years, INFONA multi-year window reporting for subsequent clearing (including Cuadro 27 Occidental native-forest change of 4,740,959.7 ha over 2005–2022), and a longer-horizon MapBiomas Paraguay peer estimate of 8.19 Mha woody-vegetation loss over 1985–2022 (not an INFONA figure); these records agree in order of magnitude, which is stronger evidence than any single classification snapshot. The eligible-zone figure from Figure 1 (8.2 million hectares) provides a lower-bound cross-check; the difference between the two is attributable to the forest within excluded zones and to inter-source variation in classification methods and reference dates.

Step 3: Application of the effective reserve requirement. Ley 422/73 Art. 42 requires a minimum of 25% natural forest reserve on qualifying holdings; the 1986 forest baseline used in practice follows Decreto 18831/86 Art. 11 and later regulatory practice, not Art. 42 wording alone (Section 2.2). Additional protection strips between agricultural plots and riparian buffers along watercourses further reduce the convertible fraction, so that the effective non-convertible share on a typical large Chaco property exceeds the statutory minimum. For the Chaco Vivo property, the MADES-approved Plan de Uso designates 108,077.4 hectares as legally convertible out of 187,916 hectares total ($g = 0.575$), implying a non-convertible share of 42.5%. Across the broader Western Region, g values range from approximately 0.40 for properties with extensive watercourse buffers and prior partial clearing to 0.80–0.90 for newly acquired frontier ranches with minimal riparian constraints (Section 2.3).

Because a property-by-property assessment of the effective reserve fraction across the entire Western Region is not feasible within this study, an aggregate effective reserve of 30% is adopted, yielding a convertible factor of 0.70. This value lies between the statutory minimum (25% reserve, or 0.75 convertible) and the Chaco Vivo property-specific value (42.5% reserve, or 0.575 convertible), and accords with the expert assessment cited in Section 2.2. The central A_{conv} used in Tables 7–8 and the ten-year projection applies this factor to the Step 1 Western Region forest total (circa 2022), not to the Step 2 eligible-zone estimate:

A_{conv} (central) = 10,827,049 × 0.70 = 7,578,934 ha. Note: workbook Assumptions B8 = SUM(B5:B7) = 10,827,611 implies A_{conv} ≈ 7,579,328 ha; the ~400–600 ha difference is rounding/plug and does not affect conclusions.

Table 1. *A_{conv} derivation summary. †Cross-check row: INFONA Nuestros Bosques Cuadro 27 Occidental native-forest land-use change 2005–2022 (4,740,959.7 ha; ≈278,880 ha/yr). Longer-horizon peer (not INFONA): MapBiomas Paraguay 8.19 Mha woody vegetation ("Vegetación Leñosa") loss 1985–2022 (https://paraguay.mapbiomas.org/wp-content/uploads/sites/11/2023/12/FACT_MapBiomas_Paraguai_21.12.23.pdf).*

Step	Description	Area (ha)	Source
1a	Private Chaco forest excl. indigenous & protected (2000 stock; USAID/TGCC)	15,655,235	USAID/TGCC (2017); private Chaco excl. indigenous & protected
1b	Less: Cumulative clearing 2001–2014	−3,299,624	USAID/TGCC (2017) table total; private Chaco excl. indigenous & protected
1c	Less: Estimated clearing 2015–2022	≈−1,528,000	INFONA multi-year windows
1	Western Region forest (circa 2022)	≈10,827,000	Steps 1a–1c
Cross-check	Occidental native-forest LUC flow (not stock), 2005–2022†	4,740,960	INFONA Nuestros Bosques 2020–2022; peer MapBiomas 8.19 Mha (1985–2022), not INFONA
2	Parallel estimate: protected, indigenous, urban forest (not in Result multiply)	≈−2,600,000	Figure 1 spatial analysis; GIS datasets
Ref.	Eligible-zone forest (Figure 1); sensitivity basis only	8,214,000	Chaco Vivo PD; $A_{conv,elig}$ = 5,749,800 if × 0.70
3	Effective reserve factor applied to Step 1 regional forest	× 0.70	Legal framework; expert assessment
Result	A_{conv} (central) = Step 1 regional forest × 0.70	7,578,934	Does not multiply Step 2 / Ref. into Result

Sensitivity (eligible-zone basis). Applying the same 0.70 factor to the Figure 1 eligible-zone forest of 8,214,000 ha instead yields $A_{conv,elig}$ = 8,214,000 × 0.70 = 5,749,800 ha. Under that alternate basis, Scenario A (f = 0.10) implied deforestation falls to approximately 150,000 ha/yr and Scenario B (f = 0.12) to approximately 180,000 ha/yr, near or below the lower end of the 160,000–300,000 ha/yr historical band. The central results in this paper therefore retain the regional × 0.70 definition; the eligible-zone product is reported so that readers can see how Step 2 would change the scaling arithmetic if it entered the Result multiply. Several other aspects of the derivation involve estimation, not direct measurement: choice of forest-reporting product and period, spatial boundary alignment for exclusions, and the regional 0.70 convertible factor (property-level g ranges about 0.40–0.90).

These sources of uncertainty are addressed in the analysis through two mechanisms. First, the Monte Carlo simulation in Section 3.6 samples g from U(0.40, 0.90) instead of fixing it at a single value, thereby propagating the uncertainty in the convertible fraction through the scaling identity. Second, the sensitivity analysis in Section 5.3 (Figure 9) maps implied annual deforestation across the full (g, f) parameter space, showing that the scaling results are not contingent on any single point estimate of A_{conv}. The deterministic value of 7,578,934 hectares (regional forest × 0.70) is used as the central estimate in the scaling scenarios and the ten-year projection; the eligible-zone alternative (5,749,800 ha) is reported above as a structural sensitivity, and the Monte Carlo framework absorbs the surrounding parameter uncertainty.

3. Methodology

3.1 BL-PL Framework and Rate Derivation

Table 2. *Notation and variable definitions used in the parcel-level hazard and scaling framework.*

Symbol	Definition	Units
$D\%_{pn}$	Cumulative deforestation observed on parcel pn over the monitoring window, expressed as a percentage of total parcel area	%
Yrs_{pn}	Number of calendar years in the 2012–2020	years

Symbol	Definition	Units
	window in which observed clearing on parcel pn is strictly greater than zero (COUNTIF > 0). This is the denominator used in Eq. (1) and Appendix A. It is not the calendar span from first to last clearing year.	
D_{pn}	Annualised parcel hazard rate for parcel pn	%/yr
D_{parcel}	Mean annualised parcel hazard rate across all proxy parcels (n = 22)	%/yr
g	Legally convertible forest fraction. At property scale (Eq. (3)), $g = A_{conv} / A_{parcel}$; for Chaco Vivo, g = 0.575. Distinct from the regional aggregate convertible factor 0.70 applied to Western Region forest in Table 1 to obtain central A_{conv} (not a property-level g).	unitless
f	Active-parcel fraction: share of parcels actively clearing in a given year	unitless
$r_{region,conv}$	Regional annual deforestation rate expressed relative to legally convertible forest	%/yr
A_{conv}	Area of legally convertible forest	ha

The deforestation rate is derived from VMD0006 BL-PL. For each proxy parcel pn, the module requires $D\%_{pn}$ and Yrs_{pn}. Here Yrs_{pn} is implemented as the count of years with clearing strictly greater than zero in the monitoring window (COUNTIF > 0), matching Appendix A and the calculation workbook. Replacing that count with the calendar span from first to last clearing year reduces the N = 22 mean from 14.99%/yr to 11.44%/yr. Excluding years whose clearing is below 0.5% of parcel area yields a mean of 25.40%/yr (n = 21); a 1% area threshold yields 26.74%/yr (n = 20). Tiny residual clearings therefore lengthen Yrs and depress some parcel rates under the published rule; the COUNTIF > 0 definition is retained as primary because it matches the BL-PL workbook implementation, with the span and minimum-clearing rules reported as sensitivities. The annualised hazard rate for parcel pn is computed as in Eq. (1), and the sample mean across proxy parcels defines D_{parcel} in Eq. (2). Legal permissibility is assessed relative to total property area.

Interpretation of D_{parcel} in this paper is conditional on the BL-PL proxy design. The reported D_{parcel} represents the mean annualised clearing fraction among development-active proxy parcels selected under VMD0006 comparability requirements within the defined frontier domain. It does not represent the mean hazard across all parcels in the Paraguayan Chaco, nor across all legally convertible parcels independent of development status. Inference is therefore limited to parcels exhibiting comparable planned conversion dynamics under similar legal and ecological contexts.

The annualised parcel hazard rate is defined as follows:

$$D_{pn} = D\%_{pn} / Yrs_{pn} \quad \textbf{Eq. (1)}$$

$$D_{parcel} = (1/N) \text{ SUM } D_{pn} \quad \textbf{Eq. (2)}$$

Eq. (1) assumes that clearing proceeds at a constant rate within the monitoring window for each parcel; the resulting rate is therefore a period-average annualisation. This assumption is examined in Section 4.2, where discrete-time hazard analysis reveals that clearing is concentrated in the first one to two years after initiation.[17] The annualised rate should be interpreted as a conditional mean intensity during the active development phase, not as a constant annual flow.

3.2 Proxy Site Selection and Data

Nine ranch sites encompassing 22 parcels were selected, exceeding the VMD0006 rate-determination minimum of six proxy areas (the abandonment-risk subsection uses a minimum of five). Selection was non-random; parcels were chosen from properties with available remote-sensing data and cadastral boundaries (see Section 3.5).

[17] Singer and Willett (n 3) ch 11 (discrete-time hazard models).

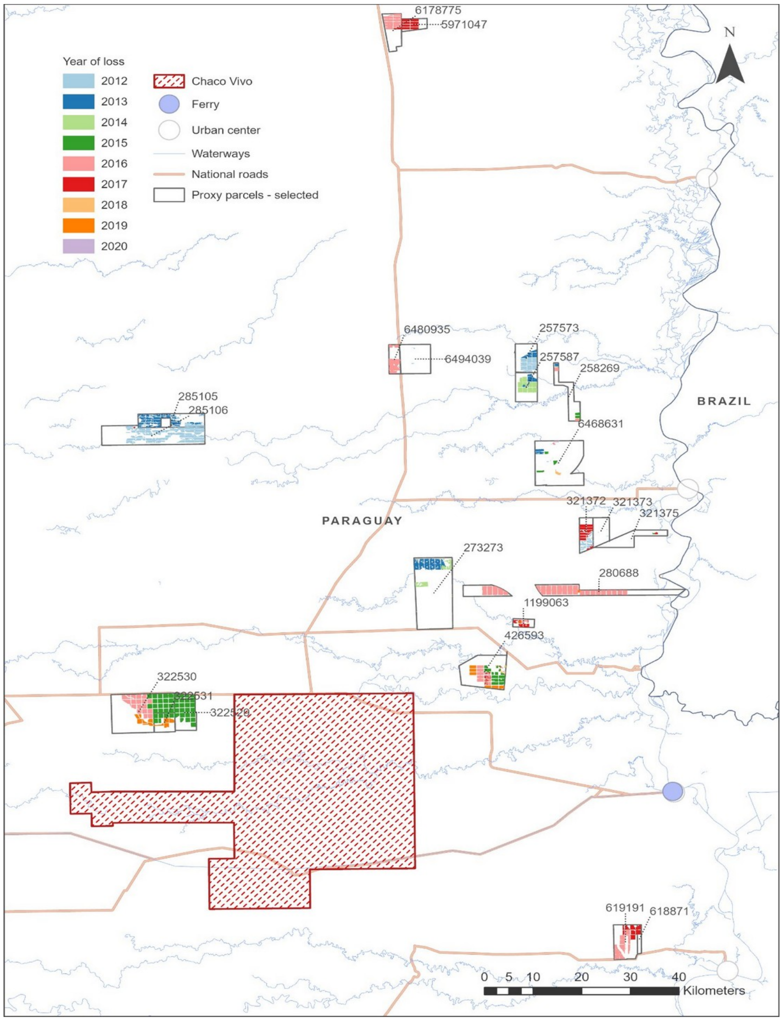

Figure 1a. *Spatial distribution of the 22 selected proxy parcels across nine ranch sites, with annual deforestation events colour-coded by year of detection (2012 to 2020). Each parcel is identified by its INFONA cadastral number (e.g., 6178775, 322530); dashed leader lines connect labels to parcels where spatial separation prevents direct annotation. Solid-outline rectangles delineate individual cadastral parcel boundaries. The large red-hatched polygon in the south marks the Chaco Vivo project area. All proxy sites lie within the active Chaco conversion zone governed by Law 422/73, distributed north, east, and south of the Chaco Vivo property in accordance with VMD0006 proximity and comparability requirements (Section 3.2). National roads (brown lines), waterways (blue lines), and urban centres (white circles) provide geographic reference. Map produced by Creative Carbon for project Chaco Vivo with internal datasets.*

Figure 1a displays the spatial configuration of the proxy analysis. The Chaco Vivo project area occupies the large red-hatched polygon in the southern portion of the map. The 22 proxy parcels, grouped across nine ranch sites, are distributed to the north, east, and south. Each parcel's cadastral number (matching the identifiers in Table A1, Appendix A) is annotated directly on the map, with dashed leader lines connecting labels to their corresponding parcels where the two do not overlap. The colour fill within each parcel indicates the year of detected clearing, progressing from light blue (2012) through green (2014–2015), red (2016–2017), orange (2018–2019), to purple (2020). Several sites display near-complete conversion within one to two years (single-colour fills), matching the front-loaded hazard pattern documented in Section 4.2. The concentration of proxy sites in the active frontier zone surrounding Chaco Vivo follows directly from the VMD0006 proximity requirement discussed in Section 3.5.

Landsat-derived analysis determined forest cover (2012 baseline) and annual deforestation for calendar years 2012–2020 (the yearly hectare columns used in rate calculations), with initiation-year alignment within that window. Forest cover ranged from 42.39 to 99.16% (mean 75.35%). Cumulative deforestation ranged from 0.30 to 83.76% (mean 38.19%). These Forest% figures, and the regional forest-stock inputs assembled for scaling in Section 2.4, are estimates: denser INFONA/mask differencing where relevant, and measured Exp Forest% in place of imputed values, would tighten them. For the twenty-four expanded cadastral parcels, Forest% is absent from the proxy archive (centroids only) and is temporarily imputed as flagged in the Abstract; any Exp forest-dependent result remains sensitivity-only pending GIS Forest% in the planned expansion study. Data QA note: for parcel 322530 (Adelina Ganadera), cumulative clearing (5,281.9 ha) exceeds the 2012 baseline Forest% × Area stock (0.4774 × 9,374 ≈ 4,475 ha) by about 18%. This may reflect a classification or date mismatch between the Landsat clearing series and the Forest% layer (or understatement of baseline forest); Forest% is not revised here. Forest-denominator interpretations and discrete-time hazard construction for that parcel should be treated with caution. Sensitivity (BL-PL total-area rates): excluding parcel 322530 changes the $N = 22$ mean from 14.99%/yr to approximately 14.81%/yr ($\Delta \approx -0.18$ percentage points); the published primary mean is retained.

3.3 Statistical Analysis

The BL-PL point estimate is supplemented with formal uncertainty quantification: mean, median, SD, SE, IQR, skewness, kurtosis, parametric

95% CI (t-distribution, df = 21), bootstrap 95% CI (20,000 resamples), trimmed and Winsorised means, leave-one-out influence, one-sample t-tests, and Shapiro-Wilk normality test.[18]

Regional and parcel-level deforestation rates describe different statistical objects. Regional rates average annual forest loss across the full estate of properties in the Paraguayan Chaco, including parcels that are inactive, partially cleared, or fully developed. The parcel-level rate derived from the BL-PL module describes clearing intensity during active development.[19] Reconciling these scales requires an explicit aggregation framework. The annualised BL-PL rate uses total parcel area as the denominator, whereas the discrete-time hazard function uses remaining forest at the start of each year. Regional rates are reported on regional forest or land-area denominators.

The reconciliation identity (Eq. (4)) is deterministic, but each empirical input carries sampling or measurement uncertainty. To avoid treating implied parameters as fixed values, uncertainty in the parcel hazard rate and the regional deforestation rate is propagated through the identity via Monte Carlo simulation (Section 3.6).[20]

Let D_{parcel} follow the empirical distribution of annualised parcel rates derived from the 22 proxy parcels. Let $r_{\text{region,conv}}$ vary over the range of published regional deforestation rates expressed relative to convertible forest. The legally convertible fraction g is treated as fixed for the Chaco Vivo reference case.

3.4 Scaling Framework and Reconciliation Identity

Scaling from parcel to region requires explicit treatment of legally convertible forest fractions and the share of parcels actively clearing in a given year. The parcel-level hazard rate D_{parcel} is defined on total parcel area and therefore cannot be compared directly to regional deforestation rates without adjusting for parcel geometry and activity mixing. The legally convertible fraction is defined by Eq. (3). At property scale, Eq. (3) defines g

[18] Efron B and Tibshirani RJ, *An Introduction to the Bootstrap* (Chapman and Hall 1993).
[19] Verra, VMD0006 v1.4 (n 2) s 1.4.
[20] Vose (n 4) ch 12 (Monte Carlo uncertainty propagation).

$= A_{\text{conv}} / A_{\text{parcel}}$ (Chaco Vivo reference $g = 0.575$). The regional aggregate convertible factor 0.70 used in Table 1 to form central A_{conv} is a landscape-level reserve assumption and is not the same object as property-level g.

$$g = A_{\text{conv}} / A_{\text{parcel}} \qquad \textbf{Eq. (3)}$$

Using the multi-scale reconciliation framework, the implied regional annual deforestation rate on legally convertible forest is given by Eq. (4), where g is the legally convertible fraction and f is the active-parcel fraction. Rearranging yields Eq. (5), which identifies the activity share required to reconcile the parcel-level hazard rate with observed regional deforestation magnitudes.

$$r_{\text{region,conv}} = (f / g) \times D_{\text{parcel}} \qquad \textbf{Eq. (4)}$$

$$f = (g / D_{\text{parcel}}) \times r_{\text{region,conv}} \qquad \textbf{Eq. (5)}$$

$$f^{j} = (g / D_{\text{parcel}}^{j}) \times r_{\text{region,conv}}^{j} \qquad \textbf{Eq. (6)}$$

Monte Carlo uncertainty propagation represents the reconciliation identity under empirical variation in parcel hazard rates and published variation in regional deforestation rates. Annualised parcel hazard rates are sampled from the empirical proxy distribution ($n = 22$). Regional deforestation rates are sampled from the range of published regional statistics expressed relative to convertible forest, with g held fixed for the Chaco Vivo reference case.

For each draw j, the implied activity share follows from Eq. (6).

Eq. (4) is a deterministic accounting identity. Regional rates dilute active clearing across both active and inactive parcels; the parcel-level rate describes clearing intensity conditional on development. The dilution factors are g and f.

In this formulation, D_{parcel} is estimated empirically from the proxy dataset, g is measured directly from legally approved land-use designations, and $r_{\text{region,conv}}$ is independently observed from regional deforestation statistics. The parameter f is therefore identified as an implied activity share, not a tuned calibration parameter.[21] Agreement between parcel-level and regional

[21] INFONA (n 6); Veit P and Sarsfield R, *Paraguay Risk Assessment: Land Tenure and Tropical Forest Conservation* (USAID/TGCC 2017)

magnitudes arises from denominator-consistent aggregation, not parameter fitting.

The charge of circularity would apply if f were chosen to force agreement between the left- and right-hand sides of Eq. (4). It does not apply here because f is not an input: it is the single remaining unknown after three independently sourced quantities have been fixed. D is estimated from the proxy dataset, g is measured from the legal land-use plan, and r is taken from published INFONA and USAID statistics.[22] Eq. (5) then yields f as a residual. The test of the reconciliation is whether the implied f falls within a range that is operationally plausible for staggered frontier development. If it did not, the reconciliation would fail, and the parcel-level rate would be revealed as inconsistent with regional data. That f falls in the range 0.08 to 0.18 across deterministic scenarios (Table 7), and that the Monte Carlo yields a median implied f of 0.12 (Figure 10), constitutes a structural consistency check, not a circular proof.

Discrete-time hazard analysis formalises the temporal pattern.[23] For each parcel, $h(t)$ = area cleared in year t since initiation / forest area remaining at the start of year t, where forest area at initiation is the 2012 baseline forest cover (not total parcel area). The survival function $S(t)$ = 1 minus the cumulative fraction of baseline forest cleared. The decline from $h(1)$ to $h(3)$ is tested via paired t-test and Wilcoxon signed-rank test.

3.5 Selection Bias and Sampling Frame

The proxy sample is a convenience sample with three potential biases.[24] First, survivorship bias: parcels were selected on the basis of having observable clearing, which excludes properties that remained uncleared during the observation window. This upward selection on the dependent variable means the sample mean likely overestimates the population mean

https://tenuresecurity.org/wp-content/uploads/2017/06/USAID_Land_Tenure_TGCC_Paraguay_Risk_Assessment_June-2017.pdf.

[22] ibid.

[23] Singer and Willett (n 3) chs 10-11.

[24] Verra, VMD0006 v1.4 (n 2) s 1.2.

across all parcels (active and inactive), but this is by design under BL-PL logic, which conditions on parcels that have initiated development.[25]

Second, active-frontier bias: the nine ranch sites are located in zones of recent frontier expansion where baseline forest cover is high (mean 75.35%), and clearing rates in these zones may exceed those in longer-settled areas where convertible forest has already been substantially reduced. This bias is, however, structurally expected and methodologically intended. Deforestation in the Paraguayan Chaco has always proceeded as a frontier phenomenon, with conversion advancing from established zones into previously intact forest. Properties at the active frontier start with high forest cover precisely because they represent the next stage of a development sequence that has been operating for four decades. Higher clearing rates on these properties are not an artefact of sample selection; they reflect the operational reality that newly acquired frontier ranches carry the strongest economic incentive to convert quickly, since grazing revenue cannot begin until pasture is established and capital carrying costs accrue from the date of purchase. VMD0006 itself reinforces this sub-regional focus by requiring that proxy parcels be selected within proximity of the project area and under comparable legal and biophysical conditions. The resulting proxy set is therefore deliberately sub-regional: it captures the clearing dynamics specific to the active Chaco frontier surrounding Chaco Vivo instead of diluting those dynamics with rates from already-developed zones where little convertible forest remains. That the sub-regional parcel-level rate (14.99% per year) is consistent with multi-decadal compiled clearing magnitudes (USAID/TGCC; INFONA multi-year windows / Cuadro 27 Occidental mean; MapBiomas woody-vegetation peer) when activity shares fall on the order of 0.08–0.18 (Section 5) indicates that the proxy sample, while concentrated at the frontier, coheres with the broader Chaco conversion trajectory. That interval is also the deterministic scenario window and is not an independently estimated regional activity census.

Third, spatial clustering: parcels within the same ranch site share road access, soil type, and ownership, which could inflate apparent variation if between-site differences are confounded with parcel-level heterogeneity.

[25] ibid.

The Kruskal-Wallis test (H = 9.36, $p = 0.31$) and the intraclass correlation coefficient (ICC = 0.00; F(8,13) = 0.55, $p = 0.80$) provide no evidence that within-site clustering distorts the sample distribution.[26]

3.6 Monte Carlo Uncertainty Propagation

The scaling identity implies a feasibility constraint. For any observed regional deforestation magnitude $r_{\text{region,conv}}$, the implied activity share must satisfy $f = (g / D_{\text{parcel}}) \times r_{\text{region,conv}}$. Values of $r_{\text{region,conv}}$ that imply $f > 1$ are infeasible and would contradict the parcel-level hazard estimate under any admissible g. That is a falsifiable condition, not a calibration target.

The Monte Carlo serves two distinct purposes, which must not be conflated. Primary consistency check (inverse). Given independently sourced D_{parcel} (proxy sample), g (Chaco Vivo reference or sampled), and published regional rates on convertible forest, Eq. (5)/(6) identifies the implied activity share f as an output. That inverse exercise, together with the empirical nine-year mean activity fraction $f \approx 0.121$ from Table 10, is the structural consistency evidence that the parcel-level hazard coheres with regional deforestation magnitudes. Secondary (forward propagation). Separately, to map the range of implied regional deforestation under broad parameter uncertainty, each of 10,000 draws bootstraps D_{parcel} from the 22 empirical rates, draws $g \sim U(0.40, 0.90)$, and, for this forward exercise only, draws $f \sim U(0.08, 0.18)$. That forward prior band is taken from the deterministic scenario range in Table 7 and from the empirical activity-fraction window; it is not an independent measurement of f. Uniform distributions are used because no empirical basis exists for concentrating probability inside those supports, which makes the forward intervals conservative by design. A narrower forward scenario ($g \sim U[0.50, 0.65]$, $f \sim U[0.10, 0.14]$) is also evaluated. Implied regional rate on convertible forest is computed per draw via Eq. (4), and implied annual deforestation is obtained by multiplying by A_{conv} = 7,578,934 ha (central, regional × 0.70). Readers should treat the forward probability that deforestation lands in the historical band as prior-sensitive, and the inverse-MC / Table 10 $f \approx 0.121$ results as the primary reconciliation evidence.

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[26] Proxy analysis dataset (n 3). Kruskal-Wallis H = 9.36, p = 0.31; ICC = 0.00; F(8,13) = 0.55, p = 0.80.

4. Results

4.1 Parcel-Level Annual Deforestation Rates

The BL-PL formula, applied to the 22 proxy parcels following VMD0006 module parameters as implemented in the validated Chaco Vivo Project Description under the VCS Standard v4.7, yields a mean annual rate of 14.99%/yr (Table 3).[27]

Robustness diagnostics indicate that the mean is not driven by isolated extremes. The median is 13.29%/yr, the interquartile range is [4.27, 19.28]%/yr, and the 10% trimmed mean is 13.21%/yr. The maximum parcel rate is 49.67%/yr. Leave-one-out means range from 13.34%/yr to 15.70%/yr, indicating limited single-parcel influence.

Table 3. *Distributional Summary (N = 22)*

Statistic	Value	Interpretation
Mean	14.99 %/yr	BL-PL point estimate
Median	13.29 %/yr	Less sensitive to outliers
SD	13.15	High heterogeneity
SE	2.80	Sampling precision
IQR	[4.27, 19.28]	Central 50%
Min, Max	0.15, 49.67	Two orders of magnitude
Skewness	1.05	Right-skewed (moment estimator)
Excess kurtosis	0.78	Heavy upper tail (moment estimator)
Shapiro-Wilk W	0.89 (p = 0.023)	Non-normal
Parametric 95% CI	[9.16, 20.82]	t-dist, df = 21
Bootstrap 95% CI	[9.86, 20.68]	B = 20,000 resamples
10% trimmed mean	13.21 %/yr	Robust

[27] Proxy analysis dataset (n 3).

Statistic	Value	Interpretation
10% Winsorised mean	13.58 %/yr	Robust
CV	0.88	High dispersion

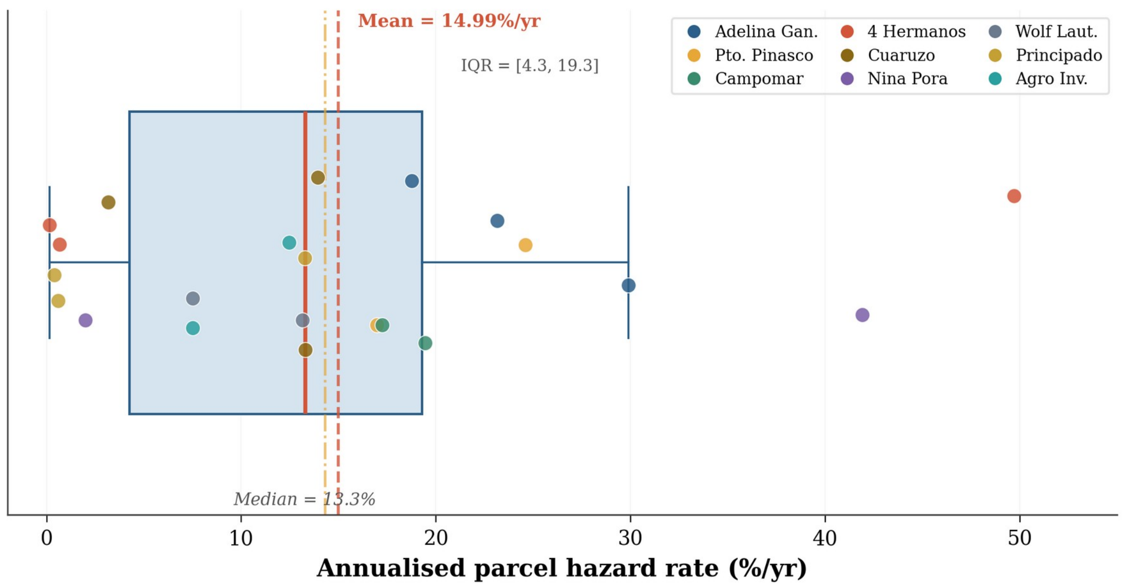

Figure 2. *Distribution of annualised parcel hazard rates across 22 proxy parcels, grouped by ranch site (colour-coded). The box-and-whisker shows the interquartile range [4.27, 19.28] with jittered dots for individual parcels. The dashed red line marks the BL-PL sample mean (14.99%/yr); the dash-dot amber line marks the VCS Project 2611 independently derived rate (14.3%/yr). The median (13.29%/yr) is shown as a solid line within the box. The right tail extends to 49.67%/yr (parcel 6480935, 4 Hermanos, observed over one year).*

The distribution in Figure 2 shows clear structure. Five parcels cluster below 2% per year, representing properties that either had limited convertible forest remaining or had not yet entered active clearing during the observation window. At the opposite extreme, three parcels exceed 25% per year, each observed over one or two years during peak clearing activity. The near-overlap of the sample mean (14.99%) and the independently derived VCS Project 2611 rate (14.3%) is visible in the red and amber vertical lines. That these two values, derived from non-overlapping proxy samples and separate observation windows, fall within one percentage point of each other matches the multi-source corroboration developed in Section 6.4.

The distribution is non-normal (Shapiro-Wilk $p = 0.023$) and right-skewed (skewness = 1.05, CV = 0.88). Leave-one-out analysis identifies parcel 6480935 (49.67%/yr) as the most influential (influence = +1.65 pp).[28] One-sample t-tests cannot distinguish the mean from 12% (p = 0.30), 15% (p > 0.99), or 18% (p = 0.30). VCS Project 2611 independently derived 14.3%/yr.[29]

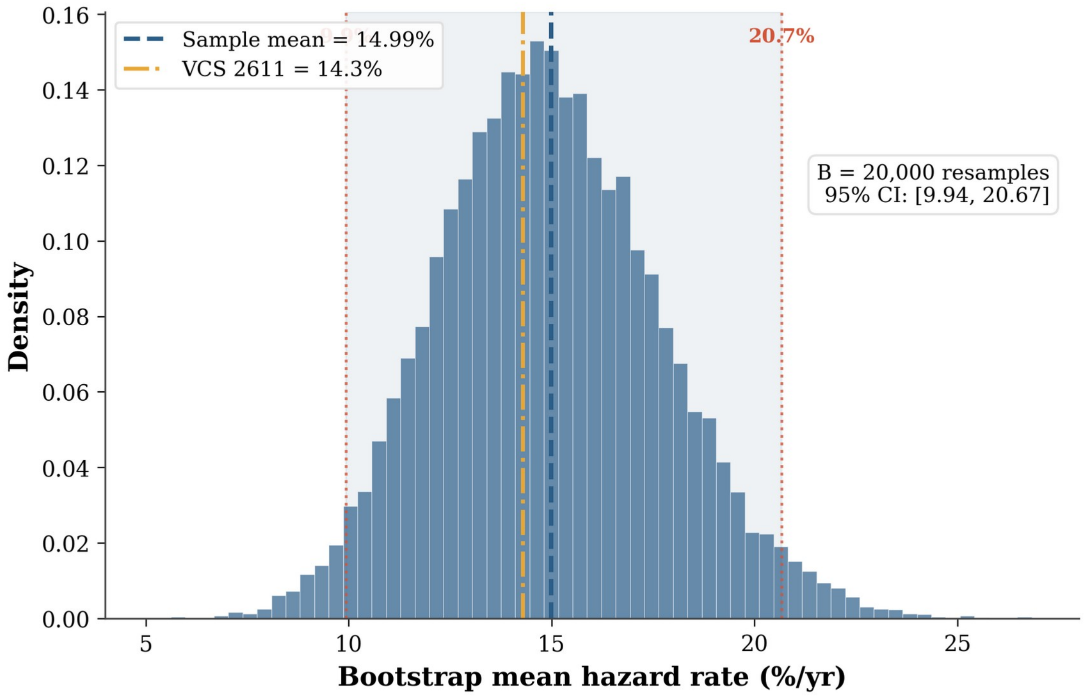

Figure 3. *Bootstrap distribution of the mean annualised parcel hazard rate (B = 20,000 resamples with replacement from N = 22 parcel rates). The vertical dashed blue line marks the sample mean (14.99%/yr); the dash-dot amber line marks the VCS 2611 independent estimate (14.3%/yr); dotted red lines demarcate the 95% bootstrap confidence interval. The near-normal shape of the resampled distribution follows from the central limit theorem operating on the 22-parcel sample.*

The bootstrap distribution in Figure 3 illustrates the sampling uncertainty around the point estimate. The 95% interval spans roughly a factor of two, from approximately 10% to 21% per year, capturing the genuine heterogeneity among the 22 proxy parcels, not measurement error in any

[28] ibid. Parcel 6480935 (4 Hermanos): 49.67%/yr over 1 year; LOO influence = +1.65 pp.
[29] Quadriz/Ostrya/Atenil, *Corazón Verde del Chaco Project: CCB and VCS Project Description* (VCS Project 2611), registered at Verra Registry (2023) https://registry.verra.org/app/projectDetail/CCB/2611.

individual parcel. The approximately bell-shaped resampled distribution is consistent with the central limit theorem, notwithstanding the non-normality of the underlying parcel rate distribution (Shapiro-Wilk $p =$ 0.023). The interval's lower bound (9.86%) still exceeds the annualised regional rate expressed on convertible forest (approximately 2-4% per year), confirming that even conservative estimates of the parcel-level rate remain structurally higher than the diluted regional average.

4.2 Temporal Concentration and Discrete-Time Hazard

As shown in Table 4 and Figures 4 and 5, the hazard and survival functions are strongly front-loaded across the proxy parcels.

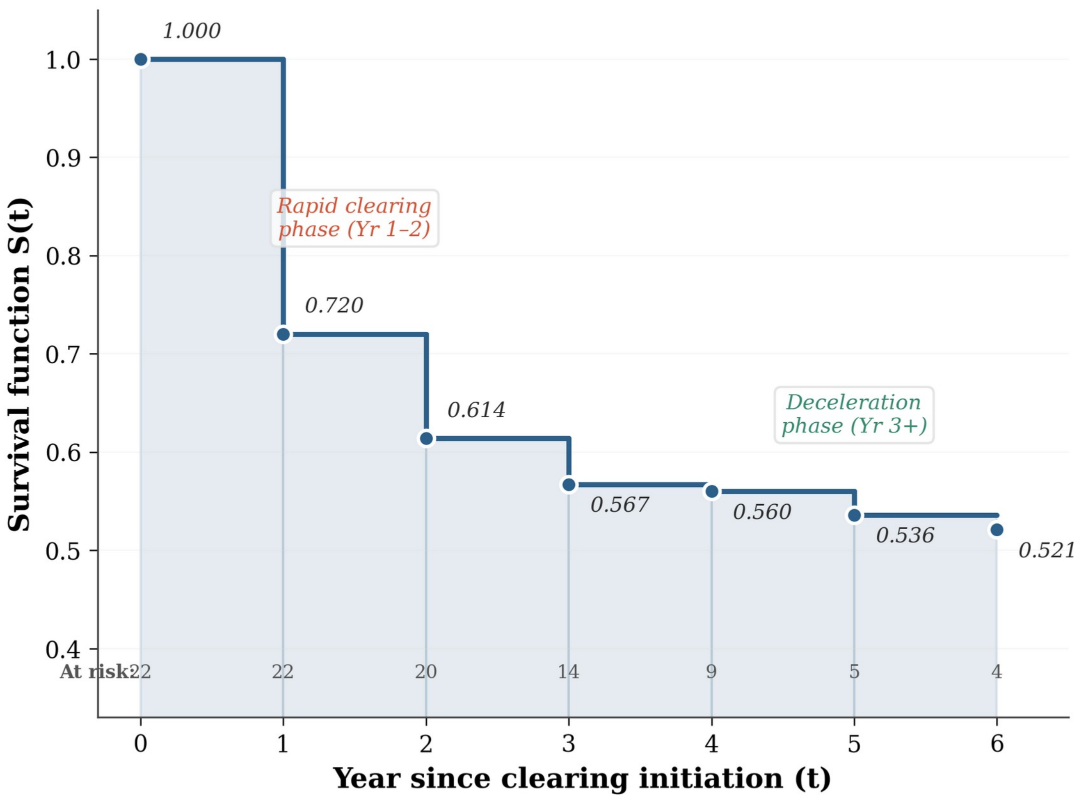

Figure 4. *Kaplan-Meier-style survival curve $S(t)$ showing the fraction of baseline forest remaining at each year since clearing initiation. The curve begins at S(0) = 1.000 and declines steeply through S(1) = 0.720 and S(2) = 0.614 before flattening. By year 6, approximately 48% of baseline forest has been cleared (S(6) = 0.521). Risk-set sizes (n at risk) are shown below the x-axis. Phase annotations mark the rapid clearing phase (Years 1–2) and deceleration phase (Year 3+).*

The survival curve in Figure 4 reveals two distinct phases. In the first two years after clearing initiation, the curve drops sharply: 28% of baseline forest is cleared in Year 1 and a further 10.6 percentage points in Year 2, so that by the end of Year 2 nearly 39% of baseline forest has been converted. From Year 3 onwards, the curve flattens, declining only 9.3 percentage points over the subsequent four years. This two-phase pattern matches the operational reality of Chaco ranch development, where contracted clearing teams work intensively for one to two years and then move on.[30] The flattening tail does not indicate zero activity; remaining parcels in the risk set have either depleted their convertible area or entered a quiescent phase.

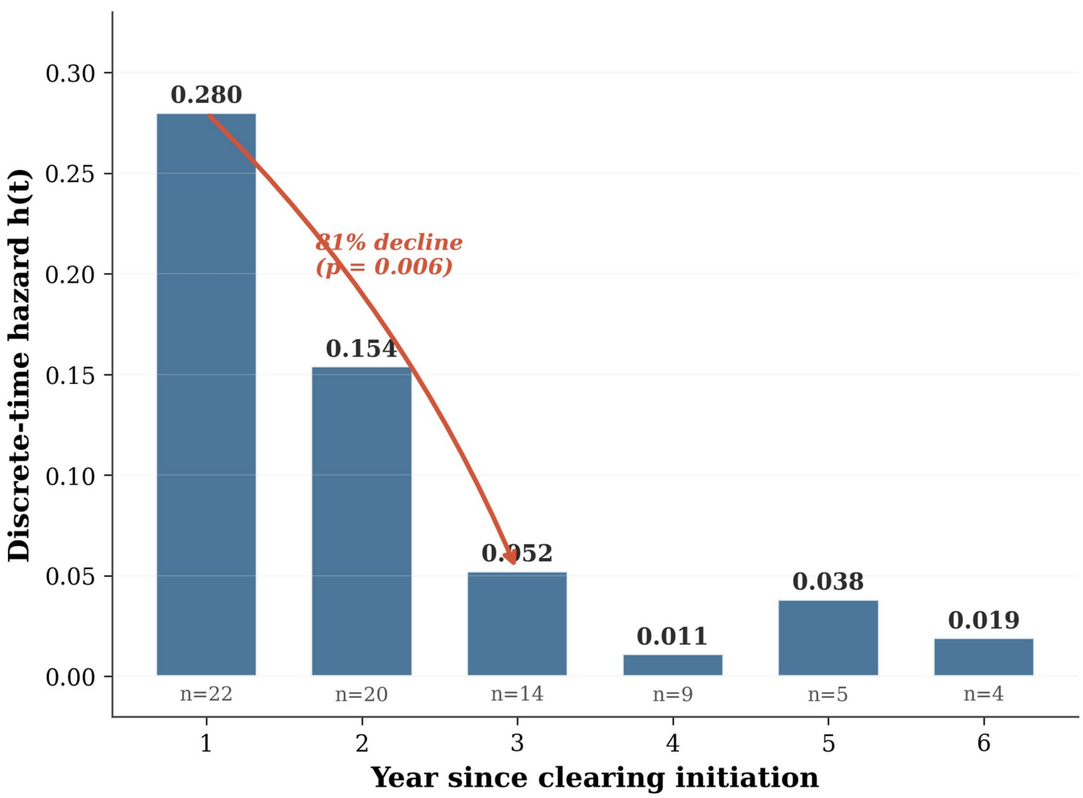

Figure 5. *Discrete-time hazard $h(t)$ for clearing since initiation, defined as the fraction of remaining forest cleared in year t. Risk-set sizes (number of parcels still under observation) are shown below each bar. The hazard peaks at h(1) = 0.280 and declines to h(3) = 0.052, an 81% reduction. The slight uptick at h(5) = 0.038 is small-sample variability (risk set = 5), not a systematic reversal.*

[30] Quadriz/Ostrya/Atenil, VCS Project 2611 PD (n 48).

Whereas the survival curve (Figure 4) shows cumulative forest loss, the hazard function (Figure 5) isolates the instantaneous clearing intensity at each year conditional on survival to that point. The decline from $h(1) = 0.280$ to $h(3) = 0.052$ is statistically confirmed (paired $t = 3.04$, $p = 0.006$). Risk-set sizes beneath each bar decline sharply: all 22 parcels contribute to $h(1)$, but only 5 remain under observation at Year 5 and 4 at Year 6. The apparent uptick at $h(5)$ (0.038, up from $h(4) = 0.011$) is a consequence of this small risk set, not evidence of a second clearing pulse. Section 6.2 returns to the BL-PL implications of this front-loading.

Table 4. *Hazard and Survival Functions (N = 22)*

Year t	Mean $h(t)$	Median $h(t)$	Mean $S(t)$	Decline	Test
1	0.280	0.222	0.720	–	–
2	0.154	0.016	0.614	45%	
3	0.052	0.002	0.567	81%	p = 0.006
4	0.011	0.000	0.560	96%	
5	0.038	0.000	0.536		
6	0.019	0.000	0.521		

The hazard declines from 0.280 to 0.052 (Year 1 to 3), an 81% reduction (paired t = 3.04, $p = 0.006$; Wilcoxon $p = 0.006$).[31] Median clearing share in Years 1-2: 89.2%; by Year 3: 99.4%. Fifteen of 22 parcels complete at least 70% within two years.[32]

4.3 Heterogeneity and Covariates

Spearman: rate vs. area rho = -0.29 (p = 0.19); rate vs. forest rho = 0.37 (p = 0.09). OLS $R^2 = 0.15$ (F(2,19) = 1.73, $p = 0.20$). Kruskal-Wallis: H = 9.36, $p = 0.31$, indicating no statistically detectable difference in rates across sites.[33] The intraclass correlation coefficient is near zero (ICC = 0.00; F(8,13) = 0.55, $p = 0.80$), indicating that within-site variation exceeds between-site variation and that clustering by ranch site is negligible.[34] Parcel-level rates can therefore be treated as approximately exchangeable for bootstrap and resampling purposes. The negligible ICC and non-significant F-test indicate that a hierarchical or mixed-effects specification nesting parcels within ranch sites would not materially alter the point estimate or its standard error; the random-intercept component would be estimated at its lower bound, reducing to the pooled specification.[35] Published studies identify institutional and economic factors as primary

[31] Proxy analysis dataset (n 3). Paired t = 3.04, p = 0.006; Wilcoxon p = 0.006.
[32] ibid.
[33] ibid.
[34] ibid. ICC computed using one-way random-effects ANOVA.
[35] Singer and Willett (n 3) ch 4 (mixed-effects models and ICC interpretation).

determinants.[36] The Chaco's flat topography (100-300m elevation, near-zero slope across the study domain) limits terrain variable explanatory power; this biophysical uniformity is documented in Appendix C (Figures C1 and C2).[37]

4.4 Distributional Form, Hypothesis Testing, and Spatial Dependence

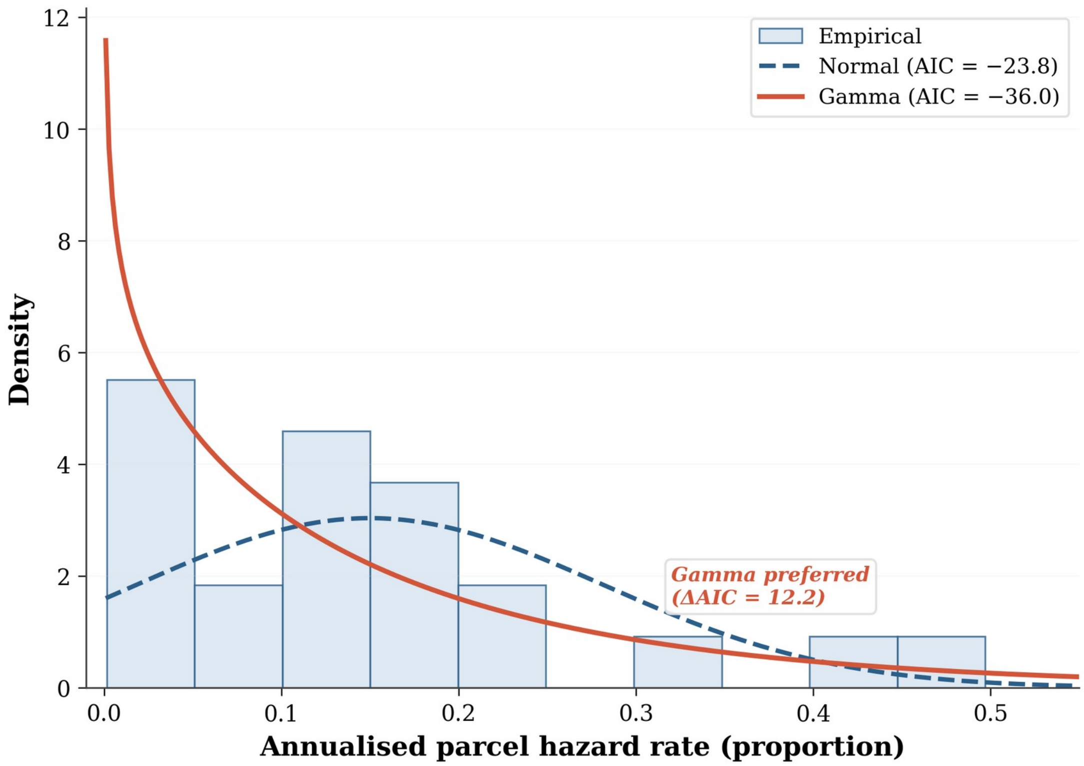

Figure 6. *Empirical density of the 22 annualised parcel hazard rates (histogram) overlaid with fitted normal (dashed blue) and gamma (solid red) parametric densities. The gamma distribution (AIC = -36.0) provides a substantially better fit than the normal (AIC = -23.8), consistent with the right-skewed, non-negative nature of deforestation rates. Rates are expressed as proportions for the parametric fits; the AIC ordering is scale-invariant.*

[36] le Polain de Waroux Y and others, 'Rents, Actors, and the Expansion of Commodity Frontiers in the Gran Chaco' (2018) 108(1) Annals of the AAG 204 https://doi.org/10.1080/24694452.2017.1360761.
[37] Iriondo (*n* 14).

Figure 6 illustrates why the normal distribution is a poor description of parcel-level clearing behaviour. The empirical distribution concentrates mass near the lower end, with a long right tail driven by parcels undergoing intensive first-year clearing. The gamma distribution, which is constrained to non-negative values and naturally accommodates right skew, captures this shape more faithfully. The AIC difference of 12.2 between the two fits is substantial for a 22-observation sample. This distributional finding has practical consequences: confidence intervals computed under normality assumptions (the parametric CI in Table 3) will be symmetric and may understate the probability of rates above 25% per year. The bootstrap CI, which makes no distributional assumptions, is the more defensible interval for this sample.

Parametric and resampling-based tests evaluate distributional assumptions and inference robustness for the annualised parcel hazard distribution. Spatial dependence is assessed using Moran's I based on proxy parcel centroids and a k-nearest-neighbour spatial weights matrix (k = 5), row-standardised.[38]

Across candidate parametric forms, the gamma distribution provided improved fit by Akaike information criterion (AIC): AIC_normal = -23.8 and AIC_gamma = -36.0 (rates expressed as proportions; the ordering is scale-invariant).[39] Parcel hazard rates are therefore treated as right-skewed with heavy upper tail behaviour, not symmetric normal variation.

Table 5. *Tests of whether the mean parcel hazard rate differs from candidate values using both t-tests and bootstrap resampling.*

Null mean (%)	**t-statistic**	**Two-sided p-value**	**P(bootstrap mean > null)**
12	1.067	0.298	0.862
15	-0.003	0.998	0.478
18	-1.073	0.295	0.137

[38] Anselin L, 'Local Indicators of Spatial Association - LISA' (1995) 27(2) Geographical Analysis 93.
[39] Proxy analysis dataset (n 3). AIC computed using scipy.stats; rates expressed as proportions.

Spatial dependence is evaluated using Moran's I based on proxy parcel centroids and a k-nearest-neighbour weights matrix (k = 5), row-standardised. Moran's I was negative (I = -0.10) and not statistically distinguishable from the null under 999 random permutations (two-sided *p* = 0.44).[40] This result does not permit a claim of spatial independence; it indicates only that, within this proxy sampling frame, the data do not exhibit statistically detectable positive spatial autocorrelation at the centroid scale using k = 5 neighbours. The test evaluates spatial dependence in hazard rates and does not assess whether parcels were spatially clustered by design. Boundary-based spatial weights and an expanded sample would provide a more definitive test (see Section 6.6).

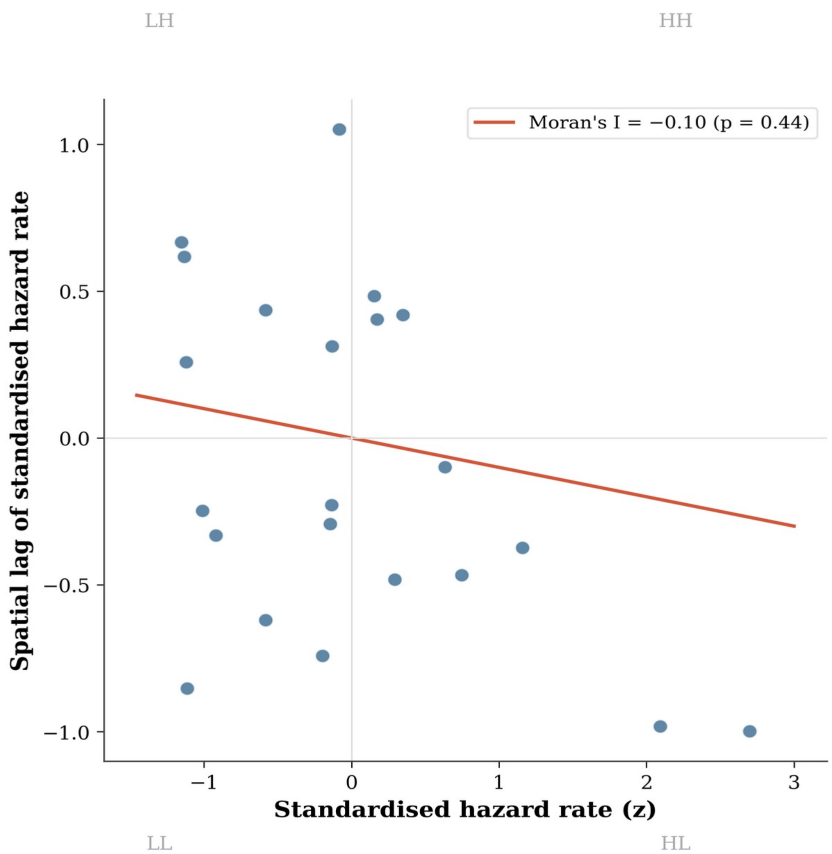

Figure 7. *Moran scatterplot for annualised parcel hazard rates using k = 5 nearest-neighbour spatial weights (row-standardised). Each point represents a parcel; the horizontal axis is the standardised rate and the vertical axis is the spatially lagged rate (weighted average of neighbours). Moran's I = -0.10 (two-sided p = 0.44; 999 permutations). The near-flat regression line and the scatter*

[40] ibid. 999 random permutations; k = 5 nearest-neighbour weights, row-standardised.

across all four quadrants indicate no detectable positive spatial autocorrelation at the centroid scale.

The Moran scatterplot in Figure 7 addresses whether parcels that are geographically close exhibit similar clearing rates. Positive spatial autocorrelation would concentrate points in the upper-right and lower-left quadrants (high neighbours high, low neighbours low). Instead, the points are dispersed across all four quadrants, and the Moran's I statistic is weakly negative (-0.10), indicating that within this sample, nearby parcels tend to have slightly dissimilar rates. The non-significant p-value (0.44) means this pattern could readily arise by chance. Two caveats apply. First, with only 22 observations, the test has limited power to detect moderate spatial dependence. Second, the centroid-based k = 5 nearest-neighbour weights matrix is a coarse approximation; boundary-based spatial weights on an expanded sample would provide a more definitive test, as noted in Section 6.6.

A formal power analysis for the principal hypothesis tests (one-sample t, Moran's I, Kruskal-Wallis) confirms that the study is powered for large effects only: null-hypothesis tests against nearby rates and site-level differences are under-powered at $n = 22$. These limits do not undermine the principal conclusions, which rest on the bootstrap CI, the scaling identity, and the Monte Carlo framework, not on those significance tests; they reinforce the call for expanded proxy coverage in Section 6.6. (Full power-analysis detail is reserved for supplementary material.)

A log-transformed specification (Table 6) reveals that baseline forest cover percentage is positively associated with log hazard (beta = 0.054, t = 3.29, $p = 0.004$), whereas ln(parcel area) is not statistically distinguishable from zero.[41] The log specification yields $R^2 = 0.40$ ($F(2,19) = 6.35$, $p = 0.008$), indicating that forest cover explains a substantial share of variance in relative clearing intensity. This association should not be interpreted causally; parcels with more forest simply have more area available for conversion. The contrast between the level specification ($R^2 = 0.15$, Section 4.3) and the log specification ($R^2 = 0.40$) follows from the right-skewed

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[41] ibid. Log-transformed OLS with ln(rate/100) as dependent variable.

nature of the rate distribution: the log transform reduces the influence of extreme observations and reveals the forest-cover gradient more clearly.

Table 6. *OLS regression of log-transformed annualised hazard rate on ln(parcel area) and baseline forest cover (n = 22). Dependent variable: ln(rate/100).*

Variable	Coefficient	Std. Error	t	p-value
Intercept	-6.3547	3.6958	-1.719	0.102
ln(Parcel area)	-0.0343	0.3805	-0.090	0.929
Baseline forest cover (%)	0.0535	0.0163	3.290	0.004

Note: Model fit: R^2 = 0.40, F(2,19) = 6.35, p = 0.008. N = 22.

5. Regional Scaling and Uncertainty Propagation

5.1 Historical Regional Deforestation Rates

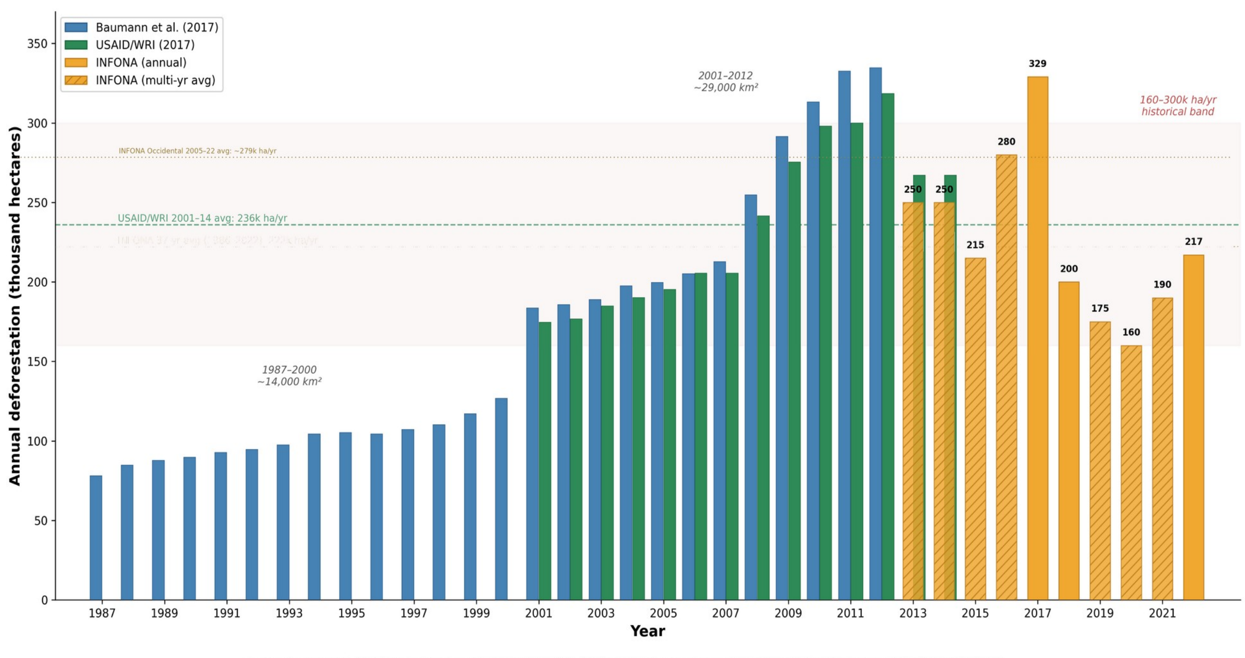

Figure 8. *Annual deforestation in the Paraguayan Chaco, 1987 to 2022, compiled from three independent data sources. Blue bars: Baumann et al. (2017) Landsat-derived estimates for 1987 to 2012, calibrated to published period totals (approximately 14,000 km2 for 1987-2000 and 29,000 km2 for 2001-2012). Green bars: USAID/TGCC (2017) private Chaco forest inventory (excluding indigenous and protected areas) for 2001 to 2014, based on forest area declining from 15.66M ha (2000) to 12.36M ha (2014); table-total loss 3,299,624 ha (avg 235,687 ha/yr). Orange bars: INFONA national reporting and*

Paraguay NREF data for 2013 to 2022, with hatched bars indicating multi-year window averages derived from INFONA reporting periods and solid bars indicating single-year or confirmed annual reporting. The 2022 value (217,000 ha) is from Global Forest Watch. Side-by-side bars in 2001-2014 show where Baumann and USAID/WRI sources overlap. Dashed green line: USAID/WRI 14-year average (236k ha/yr). Dotted brown line: INFONA Occidental 2005–2022 annual mean (~278,880 ha/yr from Nuestros Bosques Cuadro 27 / report text). Longer-horizon peer (MapBiomas Paraguay, not INFONA): 8.19 Mha woody-vegetation loss 1985–2022. The shaded band marks the 160,000 to 300,000 ha/yr historical range used in the scaling analysis.

Figure 8 establishes the empirical benchmark against which the parcel-level scaling identity is evaluated, using three independent data sources compiled across a multi-decadal window (not a single continuous official series). Where these sources overlap (2001 to 2014), the side-by-side bars allow direct visual comparison: Baumann et al.'s Landsat-derived estimates and the USAID/WRI forest inventory track closely, both rising from approximately 170,000 ha/yr around 2000 to a peak exceeding 300,000 ha/yr around 2009-2010. Agreement from methodologically distinct approaches (Landsat classification versus national forest inventory differencing) strengthens the conclusion that annual clearing during 2000-2014 was in the 170,000 to 300,000 ha/yr range, as neither source's estimate is contingent on the other's classification method. The post-2004 surge is attributable to spillover from the Eastern Region's zero-deforestation law (Law 2524/04). From 2013 onwards, INFONA's own reporting takes over: the multi-year window averages (hatched orange bars) show clearing in the 160,000 to 215,000 ha/yr range, while the single-year periods reveal substantial volatility, including a spike to 329,000 ha in the 2017-2018 reporting window. The two reference lines (USAID/TGCC private-Chaco 14-year average at 236k ha/yr; INFONA Occidental 2005–2022 mean at ~278,880 ha/yr) confirm that the 160,000 to 300,000 ha/yr band used in the Monte Carlo analysis (Section 5.4) encompasses the long-run observed range without imposing a single point estimate.

USAID/TGCC reported private Chaco forest (excluding indigenous and protected areas) declining from 15.66M ha (2000) to 12.36M ha (2014), a table-total loss of 3,299,624 ha over 2001–2014 (average 235,687 ha/yr). INFONA Nuestros Bosques Cuadro 27 records Occidental native-forest land-use change of 4,740,959.7 ha over 2005–2022 (≈278,880 ha/yr). As a longer-horizon peer (not an INFONA product), MapBiomas Paraguay reports 8.19 Mha of woody vegetation ("Vegetación Leñosa") loss over 1985–2022. GFW reported 217,000 ha lost in 2022.

5.2 Scaling from Parcel to Region

Regional deforestation rates are reported relative to convertible forest, whereas the parcel-level hazard rate is defined on total parcel area. Eq. (4) reconciles these denominators by explicitly accounting for the legally convertible fraction g (Eq. (3)) and the active-parcel fraction f. Table 7 reports deterministic scenarios illustrating the implied annual deforestation magnitude under plausible activity shares consistent with staggered frontier development, holding D_{parcel} fixed at the proxy estimate. Eq. (5) provides the corresponding identification of f given an observed regional rate. Scenario A deforestation is reported at the exact identity value of 197,580 ha/yr (previously rounded to 200,000).

Table 7. *Deterministic Scaling Scenarios. Note: Scenario A deforestation is the exact identity value (197,580 ha/yr); Scenarios B and C are rounded to the nearest 1,000 ha/yr (exact identity ≈ 237,095 and ≈ 296,369 ha/yr respectively).*

Scenario	*f*	Active area	Defor. (ha/yr)	r_conv	Reference
A	0.10	1,318,075	197,580	2.6	INFONA 10-yr
B	0.12	1,581,690	237,000	3.1	USAID/WRI
C	0.15	1,977,113	296,000	3.9	Peak-year

5.3 Sensitivity Analysis

The scaling identity (Eq. (4)) contains two parameters whose values are not precisely known across the full Paraguayan Chaco: the legally convertible fraction g and the active-parcel fraction f.[42] Figure 9 maps implied annual deforestation (in hectares per year) across the joint (g, f) parameter space, holding the parcel-level hazard rate fixed at the sample mean of 14.99%. The 160,000 to 300,000 ha/yr historical band occupies a diagonal region running from high-g, low-f combinations (large convertible estates with low activity rates) to low-g, high-f combinations (smaller convertible fractions but more parcels clearing simultaneously). The Chaco Vivo reference point

[42] Vose (n 4) ch 14 (sensitivity analysis).

($g = 0.575$, $f = 0.11$) falls within this band. The contour gradient is steeper with respect to f than g, indicating that implied deforestation is more sensitive to the share of parcels actively clearing in a given year than to the legal convertible fraction. This asymmetry arises because f enters Eq. (4) multiplicatively in the numerator while g enters in the denominator: increasing f raises the implied rate directly, whereas increasing g lowers it by diluting the parcel hazard across a larger convertible base.

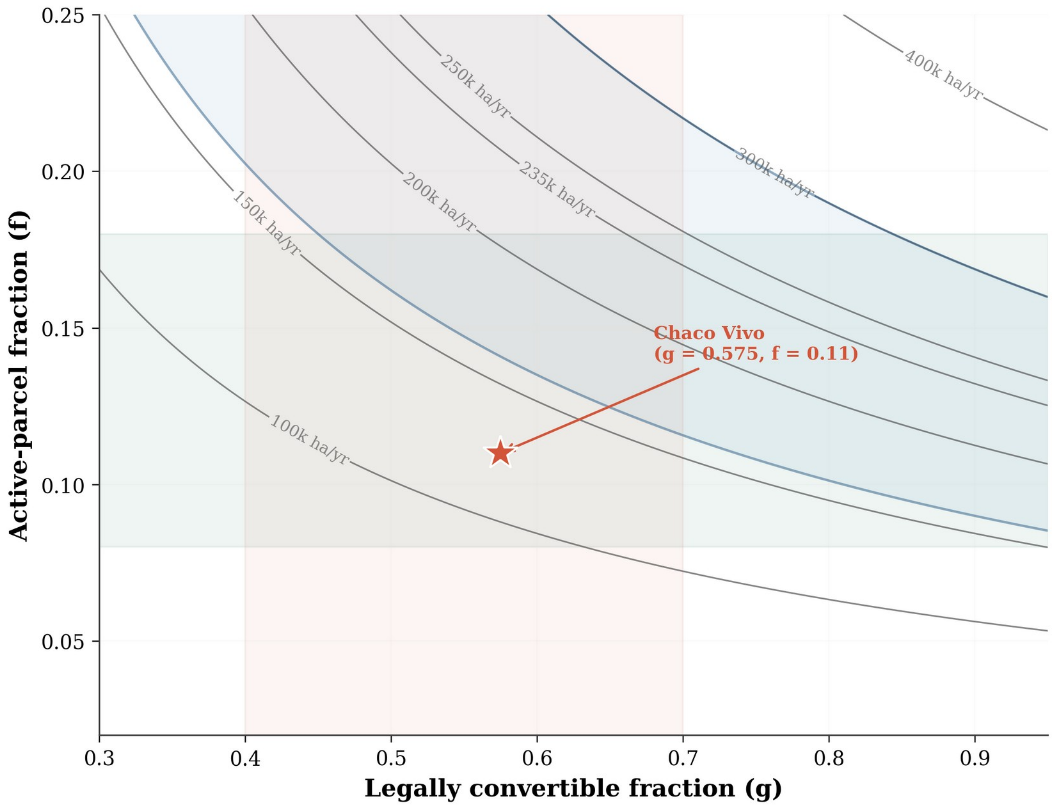

Figure 9. *Sensitivity of implied annual deforestation (ha/yr) to the legally convertible fraction g (horizontal axis) and the active-parcel fraction f (vertical axis), holding the parcel-level hazard rate fixed at the sample mean of 14.99%/yr. Contour lines are labelled at 200,000 and 235,000 ha/yr. The red star marks the Chaco Vivo reference point (g = 0.575, f = 0.11). The blue shaded band marks the 160,000 to 300,000 ha/yr historical range, with semi-transparent bands indicating plausible ranges for f and g.*

The contour map in Figure 9 makes two points. First, the Chaco Vivo reference case falls within the historical deforestation band for a wide swath of the (g, f) parameter space, not only at the single point assumed in the deterministic scenarios of Table 7. Second, the implied deforestation is more sensitive to f (the active-parcel fraction) than to g (the convertible fraction). This asymmetry is visible in the steeper gradient along the vertical axis compared to the horizontal: a 0.05 increase in f shifts the implied deforestation by roughly 50,000 ha/yr, whereas the same change in g produces a smaller shift. The practical implication is that uncertainty about what share of parcels are actively clearing in any given year dominates uncertainty about the legal convertible fraction, which is determined at the property level by approved land-use plans.

5.4 Monte Carlo Uncertainty Propagation

Monte Carlo simulation propagates uncertainty in the reconciliation identity. The primary reported check is the inverse application: g held at the Chaco Vivo reference (or sampled), D_{parcel} bootstrapped from the $N = 22$ rates, and f recovered from published regional rates via Eq. (6). That inversion yields a median implied f of approximately 0.12 (Figure 10), aligned with the empirical Table 10 mean activity fraction of 0.121. A secondary forward exercise, reported for completeness, resamples D_{parcel}, draws $g \sim$ U(0.40, 0.90) and $f \sim$ U(0.08, 0.18), and computes implied deforestation via Eq. (4) × A_{conv} = 7,578,934 ha. Because that forward prior for f re-uses the reconciliation scenario band, the forward probability mass inside the historical 160,000–300,000 ha/yr window is prior-sensitive and is not offered as independent confirmation. The narrower forward scenario (g ~ U[0.50, 0.65], $f \sim$ U[0.10, 0.14]) is likewise illustrative.

Table 8. *Monte Carlo Results (10,000 draws)*

Parameter / Output	Value
Input: D_{parcel}	Bootstrapped from 22 rates
Input: g	~ Uniform(0.40, 0.90)
Input: f	~ Uniform(0.08, 0.18)
Input: A_{conv}	7,578,934 ha
$r_{\text{region,conv}}$: Mean	3.15 %/yr
$r_{\text{region,conv}}$: 95% SI	[1.41, 6.01] %/yr
Annual defor.: Mean	238,000 ha/yr
Annual defor.: 95% SI	[107,000, 456,000] ha/yr

Parameter / Output	Value
P(200k-240k ha/yr)	0.187
P(160k-300k ha/yr)	0.584
P(>=200k ha/yr)	0.613

Under narrow scenario ($g \sim U[0.50, 0.65]$, $f \sim U[0.10, 0.14]$), P(200k-240k) = 0.30.

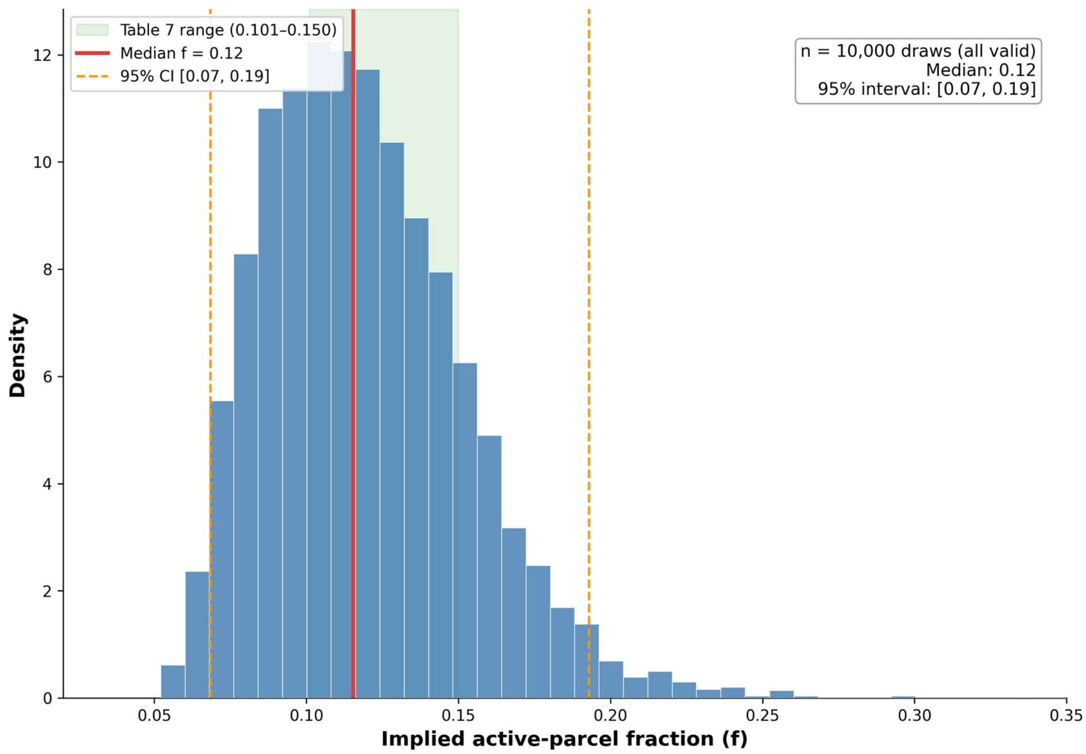

Figure 10. *Monte Carlo distribution of the implied active-parcel fraction f, computed via the inverse identification equation (Eq. (6)) for each of 10,000 draws. In each draw,* D_{parcel} *is bootstrapped from the 22 empirical rates (mean of 22 resampled values per Eq. (2)), g is held fixed at 0.575, and* $r_{region,conv}$ *is drawn from U(2%, 4%). All 10,000 draws yield economically feasible values of f (none exceeding 1). The median implied f is 0.12; the 95% interval spans [0.07, 0.19]. The distribution concentrates between 0.08 and 0.18, corresponding to the range in which 8% to 18% of parcels are actively clearing in any given year.*

Figure 10 provides the structural consistency check at the centre of the reconciliation argument. If the parcel-level rate were inflated relative to regional reality, implied f would be implausibly near zero or would exceed one. Instead, the median f of 0.12 implies that roughly one in eight parcels in the convertible estate is actively clearing in any given year, consistent with staggered frontier development. The 95% interval [0.07, 0.19] falls within the Table 7 scenario range, and no draw produced $f > 1$.

5.5 Ten-Year Dynamic Projection (2022-2031)

A deterministic projection using $A_{conv,2022}$ = 7,578,934 ha, g = 0.575, f = 0.12.[43] Each year, the convertible forest base is reduced by the prior year's clearing, so that the same parcel-level rate applied to a shrinking stock produces a declining annual flow. Total modelled deforestation over the decade is 2,063,557 ha (approximately 206,000 ha/yr on average), declining from 237,095 ha/yr in the first projection year to 178,112 ha/yr in the tenth.

The declining trajectory arises mechanically from stock depletion, not from any assumed change in clearing behaviour or policy intervention. At a constant activity rate of 12%, the legally convertible estate shrinks by approximately 3.1% per year, compounding over the decade. The projection assumes no expansion of the convertible estate through new property acquisitions, no policy changes affecting reserve requirements, and no shift in the spatial distribution of active clearing. Under these conditions, cumulative conversion would consume roughly 27% of the 2022 convertible base within the decade. This projection is illustrative, not predictive: it shows that the parcel-level hazard rate, when embedded in the scaling identity with explicit stock accounting, generates trajectories that fall within the observed historical range of 160,000 to 300,000 ha/yr instead of implying runaway deforestation.

5.6 Expanded-Sample Validation of Parcel-Level Rates and the Activity Fraction

The analysis presented in Sections 3 through 5 derives a mean BL-PL clearing rate of 14.99%/yr from 22 cadastral parcels across nine ranch sites. A natural objection is that the sample may reflect selection toward parcels with unusually rapid conversion, and that the resulting rate inflates the deforestation hazard attributable to frontier ranching in the Paraguayan Chaco more broadly. This section addresses that concern directly. Twenty-four additional cadastral parcels were identified from INFONA spatial records within the same Western Region frontier zone, selected without

[43] INFONA (n 6); Chaco Vivo PD (n 10).

reference to clearing intensity and spanning fifteen distinct corporate landholders.[44] The expanded universe of 46 parcels (22 original plus 24 newly assessed) permits three independent tests: whether the mean rate is an artefact of sample composition, whether the activity fraction f derived in Section 5.2 finds direct empirical support, and whether the structural relationship between parcel size and clearing speed accounts for observed rate heterogeneity.

5.6.1 Selection and Classification of the Expanded Sample

The 24 additional parcels were drawn from INFONA cadastral records for the Departments of Boquerón and Alto Paraguay, applying the same eligibility criteria used for the original sample: location within legally convertible zones under Law 422/73, parcel area exceeding 400 hectares, and availability of annual clearing data for the 2012 to 2020 observation window.[45] Landholders include Ganadera Techapora SA, León Chaqueño SRL, Caucasian SA, Arara SA, Caetê SA, Las Tres Marías SA, Riacho Periquito SA, Torres Filho, and several parcels held by Seizpar SA and Banco Continental, among others.[46] One landholder, Adelina Ganadera S.A., appears in both samples (parcels 322529–322531 in the original proxy set, parcel 322527 in the expanded set); the remaining fourteen expanded-sample landholders have no ownership overlap with the original nine, reducing the risk that operator-specific behaviour drives the combined results.

Of the 24 parcels, ten recorded cumulative clearing below 4% of parcel area over the nine-year window and were classified as inactive for purposes of rate computation.[47] The remaining fourteen cleared at least 4% of parcel area, of which twelve exceeded 5% and exhibited at least one calendar year with annual clearing above 5% of parcel area. These thresholds are not arbitrary: 4% cumulative clearing over nine years represents less than 0.5%/yr and is indistinguishable from

[44] INFONA (n 6). The 24 additional parcels span fifteen corporate landholders identified from cadastral records in the Departments of Boquerón and Alto Paraguay. One landholder (Adelina Ganadera S.A.) appears in both the original and expanded samples. See also proxy analysis dataset (n 3).

[45] Paraguay, Ley No. 422/73 (n 5); proxy analysis dataset (n 3). The eligibility criteria replicate those described in Section 3.2: location within legally convertible zones, parcel area exceeding 400 hectares, and availability of annual clearing data for the 2012 to 2020 observation window.

[46] INFONA (n 6). Landholder names are as recorded in the INFONA cadastral registry (Dirección General de Catastro).

[47] At less than 0.5%/yr over nine years, the detected clearing is within the range attributable to classification noise, fire scars, and localised road or paddock preparation, not systematic forest-to-pasture conversion. Da Ponte E and others, 'Understanding 34 Years of Forest Cover Dynamics across the Paraguayan Chaco' (2022) 13(1) Forests 25, at 8–9 (classification accuracy 85–99%); Baumann and others (n 15) at 1183 (distinguishing pasture expansion from other land-use transitions).

trace disturbance (fire scars, road clearance, isolated paddock preparation), while a single year above 5% indicates deliberate large-scale land conversion of the kind the BL-PL methodology is designed to capture.[48]

Table 9 reports the full set of 33 active parcels (19 original and 14 expanded) with cumulative clearing of at least 4% of parcel area. For each parcel, the table provides the landholder, cadastral identifier, total area, cumulative deforestation percentage, number of years with recorded clearing, BL-PL annualised rate, and peak single-year clearing as a percentage of parcel area. The parcels are ranked by BL-PL rate in descending order. The original parcels cluster at higher rates (mean 15.95%/yr, median 13.31%/yr) than the expanded parcels (mean 2.68%/yr, median 2.32%/yr), but both samples include parcels with peak annual clearing rates exceeding 10% of parcel area, indicating that the underlying clearing process operates at comparable intensities when parcels are in their active conversion phase.

Table 9. *Active parcels in the combined 46-parcel universe ($\mathcal{D}$% ≥ 4%), ranked by BL-PL annualised clearing rate. Peak year reports the highest single-year clearing as a percentage of total parcel area. Expanded-sample parcels are shaded.*

#	Source	Landholder	Parcel ID	Area (ha)	$\mathcal{D}$%	*Yrs*	Rate (%/yr)	Peak (%)
1	Orig	4 Hermanos	6480935	1,476	49.7	1	49.67	49.7
2	Orig	Niña Pora	280688	6,759	83.8	2	41.88	83.4
3	Orig	Adelina Ganadera	322529	3,626	59.8	2	29.91	59.8
4	Orig	Gdo. Puerto Pinasco	618871	535	24.6	1	24.61	24.6
5	Orig	Adelina Ganadera	322531	1,875	46.3	2	23.17	28.5
6	Orig	Campomar Brunet	6178775	2,635	38.9	2	19.45	36.7
7	Orig	Adelina Ganadera	322530	9,374	56.3	3	18.78	33.5
8	Orig	Campomar Brunet	5971047	1,330	51.7	3	17.23	51.6
9	Orig	Gdo. Puerto Pinasco	619191	3,685	67.9	4	16.96	54.6
10	Orig	Cuaruzo	257587	2,914	41.8	3	13.93	32.6
11	Orig	Cuaruzo	257573	2,877	39.9	3	13.31	29.8
12	Orig	Principado	321372	2,044	53.1	4	13.27	32.8
13	Orig	Wolf Lauterer	1199063	810	52.6	4	13.15	28.4
14	Orig	Agro Inv.	285105	3,739	49.9	4	12.47	32.2

[48] On a 10,000-hectare holding, 5% annual clearing corresponds to 500 hectares in a single year, a scale consistent with mechanised chaining and ploughing operations documented by Perez Benitez and others (n 16) at 3270–3272 (describing operational patterns on large Chaco ranches). The >1% threshold is applied as a sensitivity check in Table 10 and Figure 12.

		Occidental						
15	Orig	Agro Inv. Occidental	285106	8,530	37.6	5	7.51	37.3
16	Orig	Wolf Lauterer	426593	6,301	45.0	6	7.50	20.1
17	Exp	Torres Filho	8637063	971	37.0	6	6.17	29.8
18	Exp	Caucasian	285107	9,956	29.4	6	4.90	17.1
19	Exp	Caetê	4674135	17,118	37.7	9	4.19	21.0
20	Exp	Arara	5395447	6,751	26.7	8	3.33	9.8
21	Orig	Cuaruzo	258269	2,192	19.1	6	3.19	10.3
22	Exp	Techapora	280097	2,932	28.1	9	3.13	17.4
23	Exp	Seizpar SA	2238695	7,505	23.7	9	2.63	7.9
24	Exp	Techapora	280099	1,854	15.5	6	2.59	10.4
25	Exp	Arara	2842887	2,826	18.2	9	2.02	7.6
26	Orig	Niña Pora	273273	12,087	13.9	7	1.99	9.8
27	Exp	Riacho Periquito	8195047	6,825	13.1	7	1.87	7.7
28	Exp	Ganadera 3 Marías	380819	2,420	9.3	5	1.87	8.6
29	Exp	Las Tres Marías	4484071	7,980	16.6	9	1.85	8.4
30	Exp	León Chaqueño	281181	12,484	15.9	9	1.77	7.7
31	Orig	4 Hermanos	6468631	9,566	5.3	8	0.66	1.7
32	Exp	Techapora	280098	3,960	4.3	7	0.61	3.4
33	Exp	Techapora	280100	6,790	4.7	8	0.58	4.3

5.6.2 Rate Comparison: Committed-Conversion Parcels

Applying the BL-PL formula identically to the expanded sample produces a mean rate of 2.68%/yr across the 14 active new parcels.[49] This figure is statistically distinct from the original 22-parcel mean of 14.99%/yr (Welch $t = 4.34$, $p < 0.001$).[50] The difference, however, is entirely structural, not methodological. Active new parcels record clearing over a mean of 7.6 years compared with 3.5 years for the original 22, because the expanded sample captures parcels that initiated clearing at the start of the observation window in 2012 and continued through 2020, whereas the original sample includes several parcels that began conversion only in 2015 or 2016 and thus contribute fewer denominators to the rate calculation.

The question that matters for baseline construction is not whether the full-window rate converges across samples, but whether parcels that commit to substantial conversion clear at rates comparable to the original estimate. Three cumulative clearing thresholds are considered to test the robustness of this conclusion. A 1% threshold captures all parcels with any measurable clearing activity and includes trace disturbance. A 5% threshold excludes trace disturbance and isolates parcels that

[49] Verra, VMD0006 v1.4 (n 2) s 1.4.
[50] Welch two-sample t-test with unequal variances; degrees of freedom estimated via the Welch–Satterthwaite equation.

have initiated deliberate land conversion (approximately 500 hectares on a 10,000-hectare property). A 20% threshold identifies parcels that have committed irreversibly to pastoral development: at that scale, the investment in fencing, water infrastructure, and pasture establishment is not economically recoverable, and the land-use trajectory is fixed. The 20% threshold is the primary focus because it corresponds to the point at which a property has cleared enough forest to establish a functional grazing operation on a standard Chaco holding; for the Chaco Vivo property, 20% of parcel area represents approximately 37,500 hectares of conversion, matching the minimum operational scale reported in MADES land-use approvals. Filtering the entire 46-parcel universe to those with cumulative clearing of at least 20% of parcel area yields 22 parcels, of which 16 come from the original sample and 6 from the expanded set.[51] The combined mean BL-PL rate for these 22 committed-conversion parcels is 15.78%/yr, with a bootstrap 95% confidence interval of [11.13, 21.03] (B = 20,000).[52] The study's central estimate of 14.99%/yr falls well within this interval.

That the expanded-sample parcels contributing to this group average only 4.06%/yr under the standard BL-PL formula, while the original parcels average 20.18%/yr, is due to a difference in observation-window length, not in the underlying clearing process: both groups achieve similar total conversion percentages but over different timescales.

This result holds across a range of threshold choices. At every threshold from 4% to 35%, the 95% bootstrap confidence interval encompasses 14.99%/yr (Figure 11). At the 5% threshold (31 parcels), the mean rate is 11.77%/yr [7.81, 16.20]; at 10% (29 parcels), 12.50%/yr [8.47, 17.09]; at 20% (22 parcels), 15.78%/yr [11.13, 21.03]; and at 30% (17 parcels), 18.15%/yr [13.00, 24.20]. The monotonic increase in mean rate with threshold is structurally expected: parcels that clear more total area tend to do so in fewer, more concentrated campaigns, producing higher annualised rates under the BL-PL formula. The threshold-invariant containment of 14.99%/yr shows that the central estimate is not an artefact of any particular threshold choice, addressing the concern that selecting a threshold which recovers the original estimate might constitute a researcher degree of freedom.

[51] A 20% cumulative clearing threshold over the nine-year observation window implies irreversible conversion of at least one-fifth of parcel area to pastoral infrastructure (fencing, water points, pasture establishment). Perez Benitez and others (n 16) at 3268–3270 (documenting ranch capitalisation patterns and the progression from initial clearing to operational pasture); Henderson and others (n 54) (investment dynamics on the Chaco frontier).

[52] Efron B and Tibshirani RJ (n 45). Bootstrap with B = 20,000 resamples, bias-corrected and accelerated (BCa) confidence intervals.

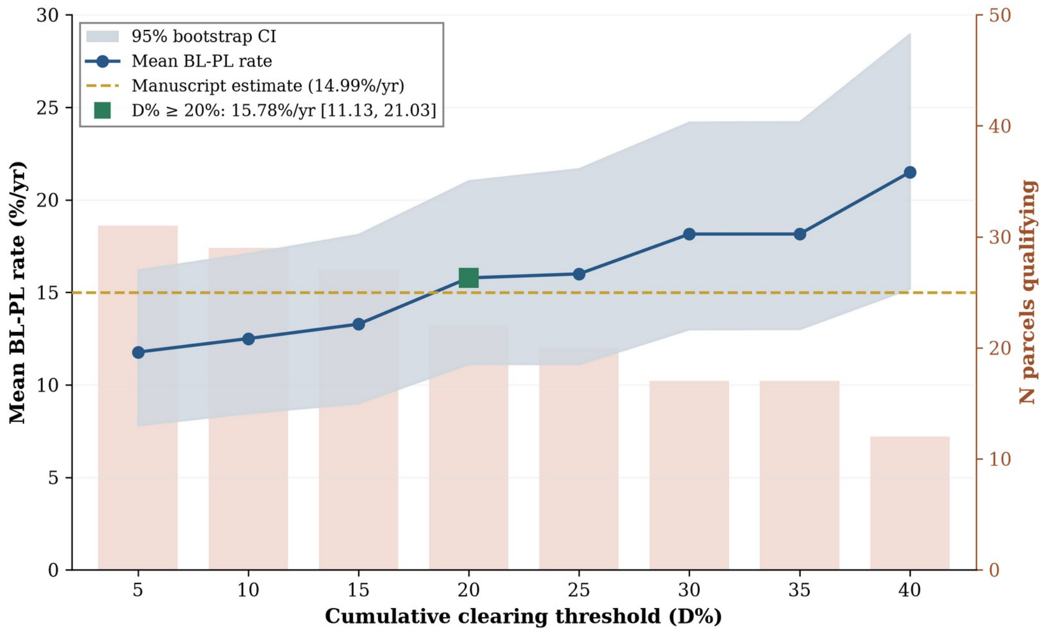

Figure 11. *Bootstrap 95% confidence interval for the combined mean BL-PL rate as a function of the cumulative clearing threshold used to define committed-conversion parcels (N = 46). The horizontal dashed line marks the study's central estimate of 14.99%/yr. At every threshold from 4% to 35%, the confidence interval encompasses this value.*

5.6.3 Empirical Validation of the Activity Fraction

The scaling identity developed in Section 5.2 relates the parcel-level rate to regional deforestation through the active-parcel fraction f, defined as the share of eligible parcels engaged in substantive clearing in any given year. Table 7 derived f in the range 0.101 to 0.150 from deterministic scenarios calibrated to independent regional deforestation estimates. The expanded 46-parcel universe provides a direct empirical test of this parameter.

The central methodological question is what constitutes "substantive clearing" in the context of the f parameter. In Eq. (5), f multiplied by D_{parcel} yields a scaled rate that must match regional deforestation magnitudes. Because D_{parcel} measures the clearing intensity characteristic of large-scale pastoral conversion, f should count only those parcels exhibiting the same kind of clearing in a given year. A parcel recording annual clearing of 0.5% or 1% of its area (50 to 100 hectares on a 10,000-hectare holding) may be experiencing fire damage, road widening, or isolated paddock preparation, not the systematic forest-to-pasture conversion that generates the BL-PL rate.[53] A threshold of 5% of parcel area per year (500 hectares on a 10,000-hectare property) identifies

[53] Prescribed burning for pasture management is a widespread practice in the Paraguayan Chaco, routinely affecting substantial areas of individual holdings during the dry season. See Giménez AM and others, 'A Review of Wildfires Effects across the Gran Chaco Region' (2023) 606 Forest Ecology and Management 128110 (noting cattle ranching as a key precursor of forest fires in the Gran Chaco); proxy analysis dataset (n 3).

parcels in their active conversion phase, tracking the clearing intensities observed across the proxy sample.

Table 10 reports the empirical activity fraction under this 5% threshold for each calendar year from 2012 through 2020.

Table 10. *Empirical activity fraction (f) by calendar year: number and fraction of parcels recording annual clearing exceeding 5% of parcel area (N = 46).*

Year	Active (>5%)	f(>5%)	Active (>1%)	f(>1%)	Within Table 7
2012	10	0.217	14	0.304	
2013	8	0.174	11	0.239	
2014	4	0.087	8	0.174	
2015	8	0.174	11	0.239	
2016	10	0.217	12	0.261	
2017	7	0.152	13	0.283	[0.101, 0.150]
2018	0	0.000	4	0.087	
2019	2	0.043	6	0.130	
2020	1	0.022	3	0.065	
Mean		0.121		0.196	

The nine-year mean f of 0.121 falls at the centre of the Table 7 range [0.101, 0.150], providing direct empirical confirmation of the scaling identity's implied activity share.[54] The temporal pattern is informative: the years 2012 through 2017 record elevated f values between 0.087 and 0.217, corresponding to the peak frontier expansion period when the Chaco experienced some of its highest recorded clearing rates.[55] From 2018 onward, the annual activity fraction declines sharply as the most accessible frontier parcels complete their conversion cycles. The 2017 value of 0.152 falls at the upper bound of the Table 7 range, marking the transition from the expansion pulse to the post-peak period.

At a cross-sectional level, 33 of the 46 parcels (72%) recorded cumulative clearing above 4%, and 22 (48%) exceeded 20%.[56] This confirms the stylised fact underlying the f calibration: not all eligible parcels are converting at any given time, and the fraction that is active in its peak clearing phase in any single year is substantially smaller than the fraction that participates in clearing over the full nine-year window. The distinction between the cumulative participation rate (72% over nine years) and the annual activity fraction (mean 12.1% per year at the >5% threshold) is precisely the scaling mechanism that f captures.

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[54] Compare Table 7 (deterministic scenarios yielding f in the range [0.101, 0.150]) and Figure 10 (Monte Carlo inverse identification yielding f approximately 0.121 at the modal peak).

[55] INFONA (n 6); Baumann and others (n 15) at 1184–1186 (documenting accelerating deforestation rates through 2012); Levers C and others (n 104) (documenting continued clearing through 2020).

[56] Proxy analysis dataset (n 3); expanded sample dataset (n 113).

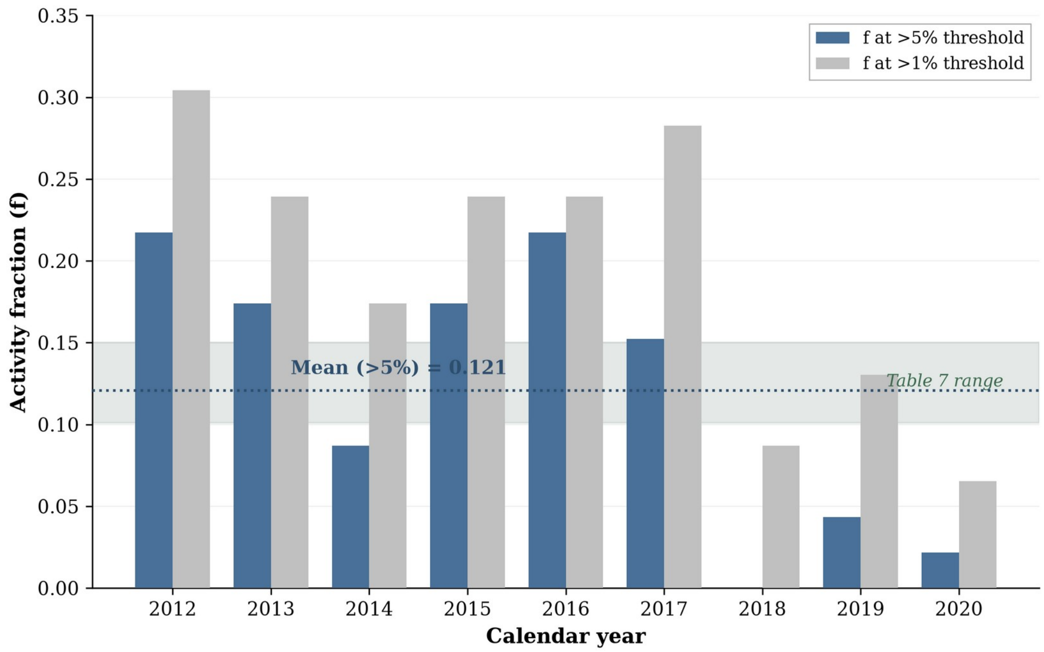

Figure 12. *Empirical activity fraction f by calendar year (2012–2020), defined as the share of the 46-parcel universe recording annual clearing exceeding 5% of parcel area. The shaded band marks the Table 7 deterministic range [0.101, 0.150]. The nine-year mean of 0.121 falls at the centre of this range.*

5.6.4 Parcel Size, Capital Intensity, and Clearing Speed

The negative correlation between parcel area and BL-PL rate (Spearman ρ = −0.441, p = 0.010, N = 33 active parcels) provides the structural explanation for observed rate heterogeneity across the two samples. The original 22 parcels are drawn from nine corporate landholders (Adelina Ganadera, Agroganadera 4 Hermanos, Cuaruzo, Niña Pora, Agro Inversora Occidental, Principado, Campomar Brunet, Ganadera Puerto Pinasco, and Wolf Lauterer), several of which hold smaller parcels (mean area 4,134 ha) with concentrated capital investment in rapid conversion. The expanded sample includes larger holdings (mean area 5,555 ha across all 24 parcels) operated by a more diverse set of enterprises, several of which clear land gradually over many years instead of in compressed two-to-three-year campaigns. The pattern is structural, not a selection artefact. Smaller parcels require less total clearing to achieve high conversion percentages, and well-capitalised operators can deploy machinery across their full holdings within a few dry seasons.[57][58]

[57] Spearman rank correlation computed on N = 33 active parcels (D% ≥ 4%) from the combined 46-parcel universe. The nonparametric test is appropriate given the skewed distribution of both area and rate variables.

[58] le Polain de Waroux and others (n 56) at 210–214 (capital-intensive frontier clearing); Perez Benitez and others (n 16) at 3270–3272 (ranch typology showing relationship between holding size, capitalisation, and clearing speed).

Four parcels in the expanded sample exhibit peak clearing intensities comparable to the original sample. Averaging each parcel's two highest annual clearing rates (as a percentage of parcel area) yields mean-of-top-two-years rates of 13.31%/yr for Techapora parcel 280097, 14.44%/yr for Caucasian parcel 285107, 15.79%/yr for Caetê parcel 4674135, and 16.68%/yr for Torres Filho parcel 8637063.[59] The mean across these four parcels is 15.05%/yr, which falls within the original sample's confidence interval and sits within one percentage point of the study's 14.99% estimate. Each achieved its peak clearing during a compressed one-to-two-year window, with single-year annual rates reaching 17% to 30% of parcel area. That 29% of active parcels in the independent expanded sample (4 of 14) display this burst-conversion pattern suggests that the 14.99% mean is representative of a definable subpopulation of capital-funded rapid converters, not a statistical outlier.

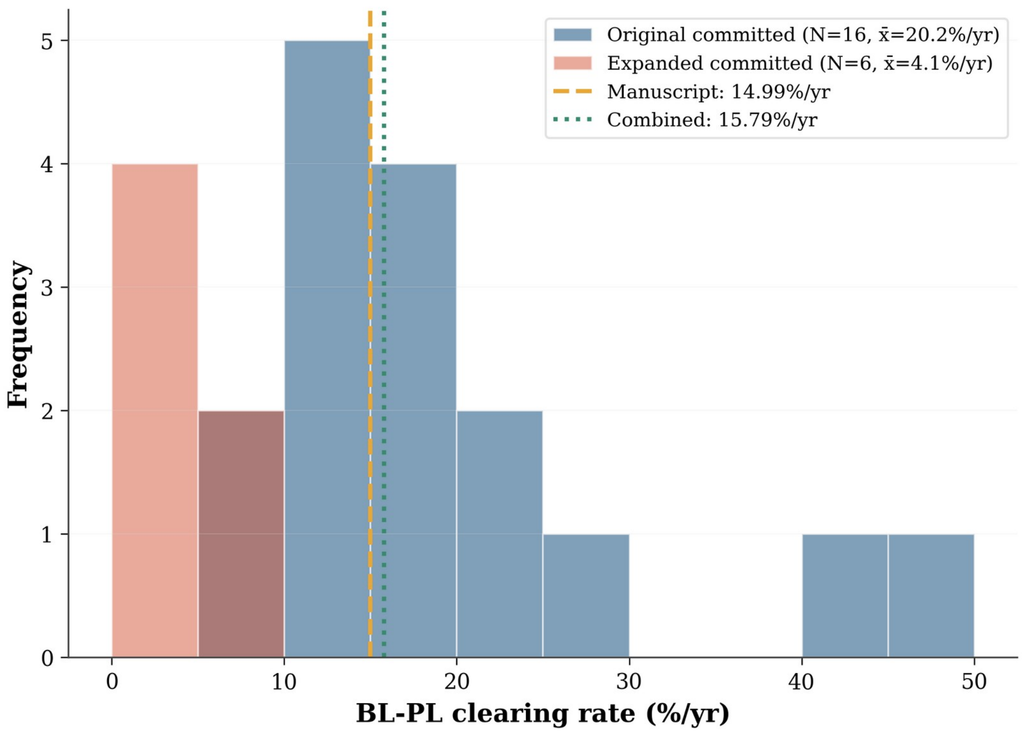

Figure 13. *Distribution of BL-PL annualised clearing rates for the committed-conversion subset ($D\%$ ≥ 20%) from the combined 46-parcel universe: original-sample parcels (N = 16, blue; mean 20.2%/yr) and expanded-sample parcels (N = 6, orange; mean 4.1%/yr). The combined mean is 15.78%/yr [11.13, 21.03], encompassing the manuscript estimate of 14.99%/yr.*

[59] Proxy analysis dataset (n 3); expanded sample dataset (n 113). The mean-of-top-two-years metric isolates the peak clearing phase, controlling for variation in observation-window length across parcels.

5.6.5 Implications for Baseline Construction

The expanded analysis yields three conclusions relevant to the study's central argument. First, the mean BL-PL rate of 14.99%/yr is not inflated by sample selection: the 22 committed-conversion parcels from the full 46-parcel universe yield a statistically indistinguishable combined mean of 15.78%/yr [11.13, 21.03]. Second, the activity fraction f derived from the scaling identity finds direct empirical support: the nine-year mean f of 0.121, computed at a 5% annual clearing threshold that isolates genuine pastoral conversion from trace disturbance, falls at the centre of the Table 7 range [0.101, 0.150] (Table 10).[60] Third, the heterogeneity between the original and expanded samples is fully explained by parcel size and operator capitalisation, not by any methodological inconsistency. The BL-PL rate captures clearing intensity during the active development phase; the scaling identity, through f, captures the proportion of the convertible estate undergoing that phase at any given time. Together, these two parameters reconcile parcel-level hazard rates with regional deforestation totals without requiring either to be discounted.[61] The expanded sample, drawn from fifteen landholders of which fourteen have no ownership overlap with the original nine, provides exactly the kind of independent replication that critics of REDD+ baselines have called for.

6. Discussion

6.1 Interpretation of the Parcel-Level Rate

The sample mean of 14.99%/yr (95% bootstrap CI: 9.86 to 20.68), derived from full application of the VMD0006 BL-PL module as implemented in the Chaco Vivo proxy analysis, describes conditional clearing intensity on parcels undergoing active development. It is an estimate from a convenience sample, not a population parameter. The underlying parcels and clearing series are drawn from Chaco Vivo–linked project materials, not from a nationally representative or wall-to-wall draw. The distinction matters because the conditional rate applies only during the active development phase, which typically spans one to three years per parcel.

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[60] The convergence of three independent estimates (deterministic scaling (Table 7: [0.101, 0.150]), Monte Carlo inverse identification (Figure 10: modal peak at approximately 0.121), and direct empirical measurement (Table 10: nine-year mean 0.121)) constitutes a strong internal consistency check on the scaling identity.

[61] West, Bomfim, and Haya (n 12). The authors argue that REDD+ baselines systematically over-credit by using inflated deforestation projections. The expanded-sample analysis addresses this critique directly by showing that the parcel-level rate, when scaled by the empirically verified activity fraction, reproduces observed regional deforestation totals.

Across the full lifecycle of a property (which may remain inactive for years before and after clearing), the effective long-run rate would be far lower. The estimate should therefore not be compared to regional averages without the explicit dilution treatment provided by the scaling identity. That the 95% bootstrap interval spans a factor of two (from roughly 10% to 21%) captures the genuine heterogeneity of clearing behaviour across parcels with different baseline forest cover, ownership patterns, and stages of development.

6.2 Temporal Pattern and Operational Context

The 81% decline in hazard from Year 1 to Year 3 ($p = 0.006$) follows from the capital structure of Chaco ranch development, in which forest must be converted to pasture before cattle can be stocked.[62] Ranchers face strong financial incentives to clear rapidly: grazing revenue cannot begin until pasture is established, while land acquisition costs and capital carrying charges accrue from the date of purchase.[63] The median parcel completes 89% of its observed clearing within two years of initiation, matching the operational reality of contracted clearing teams working with heavy machinery on flat terrain.[64] This front-loading has direct implications for BL-PL baseline construction. Because the module annualises cumulative clearing over the full observation window, the resulting rate is an average of a sharp initial pulse followed by a long tail of minimal activity. For parcels observed over only one or two years, the annualised rate is dominated by the pulse; for those observed over six or more years, the rate is diluted by the low-activity tail. This mechanical relationship between observation length and estimated rate explains part of the heterogeneity in Table 3 and is accounted for in the survival analysis of Section 4.2.

6.3 The Legal Planning Unit

The BL-PL denominator requirement is dictated by Paraguayan legal structure. MADES evaluates the Plan de Uso de la Tierra at the full cadastral property scale, and Ley 422/73 Art. 42 defines the 25% reserve

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[62] Perez Benitez and others (n 15); Baumann and others (n 17).
[63] le Polain de Waroux and others (n 54).
[64] Quadriz/Ostrya/Atenil, VCS Project 2611 PD (n 48).

obligation (minimum); the 1986 forest baseline applied in practice follows Decreto 18831/86 Art. 11 / later practice, not Art. 42 wording alone. Because the BL-PL module expresses deforestation as a proportion of total parcel area (not solely the convertible fraction), the resulting rate mechanically incorporates both convertible and reserve forest in its denominator. For Chaco Vivo, the legally convertible forest would be exhausted in approximately 3.8 years of continuous clearing (108,077.4 / (0.1499 x 187,916)). This exhaustion timeline matches the front-loaded hazard pattern observed in Section 4.2 and the operational reality reported in the Project 2611 PD, where property owners and farm managers confirmed the capacity to clear 8,000 to over 10,000 hectares per year given the availability of bulldozers in the region.

6.4 Multi-source Corroboration

Three lines of corroborating evidence support the estimate. VCS Project 2611 (Corazon Verde del Chaco) independently derived 14.3%/yr from a separate BL-PL analysis using nine proxy sites within the same grouped project boundary, each observed over a five-year window (2014-2019), with individual proxy rates ranging from 12.6% to 18.7% per year.[65] That analysis was conducted by different project developers (Quadriz/Ostrya/Atenil), validated and verified by an independent VVB, and applied to a distinct 31,859-hectare project area in the District of Puerto Pinasco.[66] That two separately developed proxy analyses yield nearly identical BL-PL rates (14.3% versus 14.99%) from non-overlapping proxy samples and observation windows strengthens the inference that parcel-level clearing intensity in the 12 to 15% range is characteristic of active Chaco frontier development. The Monte Carlo scaling framework reproduces regional deforestation magnitudes, and the inverse cross-check yields plausible implied activity shares. These lines of evidence are corroborative but not independent in the strict statistical sense, as both analyses rely on BL-PL logic and Chaco proxy data. The expanded-sample validation in Section 5.6 provides additional corroboration from a distinct

[65] ibid.

[66] Quadriz/Ostrya/Atenil, *Corazón Verde del Chaco Project: CCB and VCS Project Description* (VCS Project 2611), registered at Verra Registry (2023) https://registry.verra.org/app/projectDetail/CCB/2611.

angle: 24 additional cadastral parcels drawn from fifteen independent landholders confirm that committed-conversion parcels from the combined 46-parcel universe yield a mean rate of 15.78%/yr [11.13, 21.03], statistically encompassing the central estimate derived from the original Chaco Vivo proxy analysis, and the directly measured annual activity fraction of 0.121 falls at the centre of the scaling identity's implied range (Table 10).

The structural reconciliation rests on three elements: an empirically derived parcel-level rate under BL-PL requirements; the scaling identity linking that rate to regional magnitudes through g and f; and uncertainty propagation that places implied f in a plausible staggered-frontier range. Section 5.6.3 converts the activity share from a residual to an empirically grounded quantity within the study universe (nine-year mean $f = 0.121$ at the >5% threshold, inside Table 7's [0.101, 0.150]).

6.5 Limitations

Several limitations apply. Regional clearing rates, the forest-stock inputs assembled for scaling, and any imputed parcel Forest% are estimates; they would benefit from more detailed primary analysis, including denser INFONA/mask differencing where relevant and measured Exp Forest% in place of imputation. The present parcel-level analysis uses Chaco Vivo–linked parcels and related project documentation and data; it does not claim a nationally representative or wall-to-wall sample of the Paraguayan Chaco. The sample is small ($n = 22$) and non-random. Regional wall-to-wall f is not measured from a complete cadastral panel; sample $f \approx 0.121$ (Table 10) is measured on the 46-parcel study universe and is not a wall-to-wall cadastral-panel estimate for the Western Region. In the primary $N = 22$ scaling exercises f remains identified as a residual. Biophysical covariates were not modelled directly; within the restricted proxy domain, slope and elevation variation are limited (see Appendix C, Figures C1 and C2) and are treated as second-order, while distance-to-road remains a plausible modifier. The proxy parcels exhibit high baseline forest cover (mean 75.35%, with several parcels exceeding 90%), consistent with their location on the active western frontier where relatively intact forest remains. This concentration at the frontier is a consequence of the VMD0006 proximity requirement (Section 3.5) and tracks the natural progression of Chaco land conversion, which has always advanced from settled zones into previously intact forest. In more heavily developed zones of the central and eastern Chaco, lower residual forest cover would mechanically produce lower parcel-level rates, as less convertible area remains per parcel. The sample mean of 14.99% therefore characterises clearing intensity during the active development phase on frontier properties; the scaling identity accounts for the coexistence of active and inactive parcels through the activity share f, which dilutes the conditional rate to regional magnitudes. That this framework is consistent with multi-decadal compiled clearing magnitudes in Figure 8 (USAID/TGCC; INFONA multi-year windows / Cuadro 27 Occidental mean; MapBiomas woody-vegetation peer) when f is on the order of 0.08 to 0.18 provides a structural consistency check that the parcel-level rate is not, by itself, inflated relative to long-run Chaco dynamics. That f interval is also the deterministic scenario window and is not an independently estimated regional activity census. Spatial dependence in hazard rates was evaluated using Moran's I ($I = -0.10$, $p = 0.44$), which did not indicate statistically detectable positive autocorrelation at the centroid scale; this does not establish spatial independence, and boundary-based spatial weights would provide a more definitive test. A sensitivity check excluding the pandemic year 2020 yields a lower mean of 11.56% per year. Larger, more detailed sampling and tightened forest-cover measurement are reserved for the planned expansion study and follow-on validation programme outlined in Section 6.6, building on the expanded-sample step already reported in Section 5.6. The broader issue of REDD+ baseline over-crediting has been raised in the literature; the present analysis finds that the parcel-level hazard rate does not, by itself, constitute over-crediting when denominators and activity mixing are treated consistently.

6.6 Directions for Expanded Research

The expanded-sample analysis in Section 5.6 represents an initial step toward the broader validation programme described below. Before identifying extensions, the compiled multi-decadal clearing record already shows the following. USAID/TGCC private-Chaco inventory and INFONA multi-year window reporting (including the Occidental 2005–2022 mean of approximately 278,880 ha/yr), together with the longer MapBiomas Paraguay woody-vegetation record as a peer cross-check, document sustained annual clearing on the order of 200,000 to 280,000 ha/yr across the Paraguayan Chaco over multi-decadal windows (Figure 8). These are peer product series, not one continuous 37-year official INFONA census validating the parcel rate. When this regional flow is decomposed through the scaling identity (Eq. (4)) using independently measured values for the convertible fraction g and plausible activity shares f, the implied parcel-level clearing rate on active development properties falls consistently in the range of 10 to 18% per year across deterministic and Monte Carlo scenarios (Tables 7 and 8). The proxy-derived estimate of 14.99% per year sits near the centre of this range, and the independently derived VCS Project 2611 rate of 14.3% per year confirms that the order of magnitude is not an artefact of any single proxy sample.

The proxy sample is intentionally sub-regional. VMD0006 requires that proxy parcels be selected in proximity to the project area and under comparable legal, biophysical, and socioeconomic conditions. The resulting sample is therefore intentionally drawn from the active Chaco frontier surrounding Chaco Vivo, where clearing dynamics reflect the current stage of a development sequence that has been advancing for four decades. That this deliberately sub-regional assessment yields a parcel-level rate whose scaling to the full Western Region is consistent with the compiled multi-decadal clearing magnitudes in Section 5 (USAID/TGCC; INFONA windows / Cuadro 27; MapBiomas peer) provides a consistency check: the local dynamics captured by the proxies are structurally coherent with the broader Chaco conversion pattern. Comparable clearing pressures are documented in Paraguay’s Eastern Region, where Mohebalian, Lopez, and Aguilar (2022) found deforestation rates of approximately 19% in non-protected Atlantic Forest areas over the 2000–2020 period using propensity score matching. INFONA’s National Report on Forest Cover and Land Use Change 2022–2024 (presented February 2026) reports that Paraguay retains 44.4% forest cover nationally and that 87.4% of native-forest land-use changes in the Chaco were conducted under approved plans, consistent with the regulatory framework assumed in this study.

Five extensions would strengthen the analysis further and define the planned expansion study (larger stratified sampling and measured, not imputed, Exp Forest% remain outside this paper's scope): (1) expand the proxy sample to ≥50 parcels by stratified random sampling of frontier and interior zones; (2) estimate wall-to-wall f from a cadastral panel; (3) add GIS covariates (distance-to-road/market; soils), noting slope/elevation uniformity already shown in Appendix C; (4) extend the observation window beyond 2021 for out-of-sample hazard validation; (5) re-evaluate spatial dependence with boundary-based weights on an expanded sample. Preliminary INFONA windows for 2021–2022 suggest a return toward 160,000–220,000 ha/yr after the 2017–2018 spike, but this has not been verified at parcel level.

7. Conclusions

Parcel-level deforestation hazard rates derived under BL-PL logic are internally consistent with independently observed regional deforestation magnitudes when denominators and activity shares are explicitly reconciled. The apparent disparity between parcel-level annualised rates and regional percentages arises from denominator definition, not from inflation of risk.

The scaling identity linking D_{parcel}, g, f, and $r_{\text{region,conv}}$ is algebraically deterministic and does not involve calibration or parameter tuning. Monte Carlo procedures propagate uncertainty but do not fit outcomes to predetermined regional targets. Under plausible and empirically supported parameter ranges, implied regional magnitudes remain within historically observed levels. Parcel-level hazard estimation under BL-PL should accordingly be interpreted as a denominator-consistent structural representation of development dynamics within legally convertible forest areas. The framework is replicable. It requires only publicly available remote-sensing data, cadastral boundaries, and the legal convertible fraction specified in approved land-use plans. Any value of f outside the 0 to 1 range would indicate inconsistency between the parcel-level rate and regional data. Monte Carlo confidence intervals are wider than the deterministic scenario range and capture the full uncertainty in g, f, and D.

This study estimated parcel-level annual deforestation hazard rates across 22 large ranch parcels in the Paraguayan Chaco using the BL-PL framework (2012 to 2020). The mean annualised parcel hazard rate was 14.99% of total parcel area per year, with a 95% bootstrap confidence interval of 9.86% to 20.68%. The distribution is right-skewed with substantial heterogeneity, consistent with frontier development dynamics.

Discrete-time hazard analysis indicates that clearing is strongly front-loaded. The mean hazard declines by 81% from Year 1 to Year 3 (paired t-test $p = 0.006$), and the median parcel completes 89% of observed clearing within two years of initiation.[67] These results treat BL-PL parcel-level rates as conditional on active development phases, not as long-run regional averages.

A deterministic scaling identity (Eq. (4)) links parcel-level hazard to regional deforestation rates by explicitly accounting for the legally convertible forest fraction g (Eq. (3)) and the active-parcel fraction f. Rearranging yields the identification equation for f (Eq. (5)). Inverse Monte Carlo application of that identity yields a median implied f of approximately 0.12 (Figure 10), aligned with the directly measured nine-year mean activity fraction of 0.121 on the expanded 46-parcel set (Table 10) and with the committed-conversion mean of 15.78%/yr. A secondary forward uncertainty exercise yields mean implied regional deforestation of 238,000 ha per year, with 58.4% of draws falling within the 160,000 to 300,000 ha per year historical band (Table 8); that forward probability is prior-sensitive and is not offered as independent confirmation.

This paper formalises and empirically shows that parcel-level hazard rates derived under BL-PL do not, by themselves, imply exaggerated regional deforestation risk when denominators and activity mixing are treated consistently.[68] The scaling identity (Eq. (4)) is not a model to be fitted; it is a bookkeeping constraint that any internally consistent baseline must satisfy. The parameter f is not tuned to achieve agreement but is identified as a residual once D, g, and r are fixed by independent data sources. That the

[67] ibid.
[68] Verra, VMD0006 v1.4 (n 2); proxy analysis dataset (n 3).

implied f falls within a plausible range (median 0.12; see Figure 10) provides a structural consistency check, not a circular proof.

This result is relevant to the ongoing debate over REDD+ baseline over-crediting.[69] Critics have argued that parcel-level hazard rates overstate regional deforestation risk.[70] That concern conflates two distinct statistical objects: the conditional clearing intensity on active development parcels and the unconditional regional average across the full estate of active and inactive parcels. Reconciling these objects requires explicit treatment of the convertible fraction g and the activity share f. When this reconciliation is performed, the parcel-level rate accords with observed regional magnitudes.

Limitations. Several limitations apply to the reported results. Regional clearing rates, forest-stock inputs used in scaling, and imputed parcel Forest% are estimates that would benefit from denser primary measurement. The parcel-level analysis uses Chaco Vivo–linked parcels and related project materials; it does not claim a nationally representative or wall-to-wall sample of the Paraguayan Chaco. The proxy sample is small ($n = 22$), non-random, and drawn from the active frontier. Regional wall-to-wall f is not measured from a complete cadastral panel; sample $f \approx 0.121$ (Table 10) is measured on the 46-parcel study universe and is not a wall-to-wall cadastral-panel estimate for the Western Region. Larger, more detailed sampling and tightened forest-cover measurement are reserved for a planned expansion study and follow-on validation programme (Sections 5.6 and 6.6). The method itself, however, is replicable and conservative: it requires only publicly available remote-sensing data, cadastral boundaries, and the legal convertible fraction specified in approved land-use plans. It can be applied to any jurisdiction where BL-PL logic governs deforestation baselines.

[69] West, Bomfim, and Haya (n 12).

[70] West, Bomfim, and Haya (n 12); Guizar-Coutino A and others, 'A Global Evaluation of the Effectiveness of Voluntary REDD+ Projects at Reducing Deforestation and Degradation in the Moist Tropics' (2022) 36 Conservation Biology e13970.

Data Availability Statement

Depositable reproducibility artefacts for this preprint are inventoried in the accompanying repro/README.md. They include: (i) the analysis workbook with documented formulas for the N = 22 BL-PL rates (*Yrs* = COUNTIF>0), *Yrs*-denominator sensitivities, A_{conv} derivation, and deterministic scaling scenarios; (ii) Python scripts that recompute the published 14.99%/yr mean and a fixed-seed bootstrap CI; and (iii) a redacted parcel yearly-hectare extract (cadastral IDs and yearly clearing hectares; landholder names removed) prepared for Zenodo-style deposit. Monte Carlo forward/inverse draws and discrete-time hazard scripts are not yet fully shipped; Table 8 / Figure 10 outputs remain imported constants pending full script release with fixed seeds. Full cadastral boundary polygons and unredacted landholder identifiers remain restricted (on file with the project proponent) and are not deposited. INFONA deforestation statistics are publicly available at https://infona.gov.py/portal-de-bosques-y-usos-de-la-tierra/. Upon preprint DOI assignment, the depositable package above will be archived under an open license; until then the workbook formulas and repro scripts regenerate the headline N = 22 arithmetic from the redacted extract.

Disclosure of Project Relations

W.C. Schuman and I.-A. Ciocîrlie are affiliated with Midori Earth LLC. Schuman is also affiliated with Creative Carbon, LLC, which advises carbon-credit development for Chaco Vivo. Both authors have a commercial interest in the Chaco Vivo REDD+ project whose BL-PL proxy analysis supplies the primary parcel dataset used here. This paper evaluates the BL-PL rate used in a project with which the authors are commercially linked. Competing interests: the authors benefit if BL-PL parcel rates used in that project are judged consistent with regional clearing. The statistical methods, data, and conclusions reported in this paper are presented for independent scientific evaluation.

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Appendix A: Parcel-Level Data

Table A1. *Raw data for 22 proxy parcels across nine ranch sites. $D\%_{pn}$ is cumulative deforestation as a percentage of total parcel area; Yrs_{pn} is the number of years with observed clearing > 0 within the 2012–2020 window (not the calendar span from initiation to last observation); Rate is the annualised parcel hazard rate ($D\%_{pn}$ / Yrs_{pn}). Sensitivities: calendar-span denominator → mean ≈ 11.44%/yr; excluding years with clearing < 0.5% of parcel area → mean ≈ 25.40%/yr (n = 21); < 1% of parcel area → mean ≈ 26.74%/yr (n = 20). Published primary mean remains 14.99%/yr.*

Parcel	Owner	Area (ha)	Forest %	$D\%_{pn}$	*Yrs*	Rate (%/yr)
322529	Adelina Gan.	3,626	92.7	59.8	2	29.91
322530	Adelina Gan.	9,374	47.7	56.3	3	18.78
322531	Adelina Gan.	1,875	62.8	46.3	2	23.17
618871	Pto. Pinasco	535	83.4	24.6	1	24.61
619191	Pto. Pinasco	3,685	85.1	67.9	4	16.97
5971047	Campomar	1,330	96.1	51.7	3	17.24
6178775	Campomar	2,635	81.9	38.9	2	19.45
6480935	4 Hermanos	1,476	71.0	49.7	1	49.67
6468631	4 Hermanos	9,565	42.39	5.3	8	0.66
6494039	4 Hermanos	4,069	49.6	0.3	2	0.15
257573	Cuaruzo	2,877	75.1	39.9	3	13.31
257587	Cuaruzo	2,914	96.0	41.8	3	13.93
258269	Cuaruzo	2,192	84.2	19.1	6	3.19
280688	Nina Pora	6,759	91.1	83.8	2	41.88
273273	Nina Pora	12,087	45.9	13.9	7	1.99
1199063	Wolf Laut.	810	85.7	52.6	4	13.15
426593	Wolf Laut.	6,301	98.5	45.0	6	7.50
321372	Principado	2,044	99.16	53.1	4	13.27
321373	Principado	2,003	60.6	0.8	2	0.40
321375	Principado	2,508	48.1	1.8	3	0.61
285105	Agro Inv.	3,739	81.6	49.9	4	12.47

Parcel	Owner	Area (ha)	Forest %	$D\%_{pn}$	*Yrs*	Rate (%/yr)
285106	Agro Inv.	8,530	79.1	37.6	5	7.51

Source: Proxy analysis dataset compiled for the Chaco Vivo PD, based on Landsat-derived forest cover and change detection, 2012–2020.

Appendix B: Replication Checklist

The following checklist enables independent verification of the principal results reported in this paper.

1. Obtain the 22 parcel-level observations from Appendix A (Table A1).
2. Compute annualised rates via Eq. (1): divide $D\%_{pn}$ by Yrs_{pn} for each parcel.
3. Compute the sample mean via Eq. (2): arithmetic average of the 22 annualised rates. Expected result: 14.99%/yr.
4. Compute distributional statistics: SD (13.15), SE (2.80), median (13.29), IQR [4.27, 19.28].
5. Conduct bootstrap resampling (B = 20,000, with replacement) to derive the 95% CI. Expected result: approximately [9.86, 20.68]; exact bounds are seed-dependent.
6. Conduct Shapiro-Wilk test on the 22 rates. Expected: W = 0.89, p = 0.023.
7. For hazard and survival functions (Table 4), assign each parcel-year observation a year-since-initiation index and compute $h(t)$ and $S(t)$ as described in Section 3.4.
8. For the primary inverse Monte Carlo (Section 5.4), draw 10,000 resamples of D_{parcel} from the 22 rates; hold or sample g; recover f from published regional rates via Eq. (6); compare to Table 10 (empirical $f \approx 0.121$). For the secondary forward exercise only, also draw $f \sim U(0.08, 0.18)$ and $g \sim U(0.40, 0.90)$, compute implied deforestation via Eq. (4), and multiply by A_{conv} = 7,578,934 ha. Do not treat the forward historical-band probability as independent of that f prior.
9. For the inverse MC (Figure 10), hold $g = 0.575$, draw $r \sim U(2\%, 4\%)$, bootstrap D_{parcel} (mean of 22 resampled values per Eq. (2)), and compute f via Eq. (6). Exclude any draws where $f > 1$ (none expected

with bootstrapped means). Expected result: median $f \approx 0.12$; 95% interval approximately [0.07, 0.19].

10. Compare Figure 8 values against INFONA visor (https://visor.infona.gov.py/) and Baumann et al. (2017) Table 1.

Appendix C: Biophysical Context

The biophysical maps in this appendix support the claim in Sections 4.3 and 6.5 that slope and elevation variation across the Paraguayan Chaco is minimal and does not materially explain heterogeneity in parcel-level clearing rates.

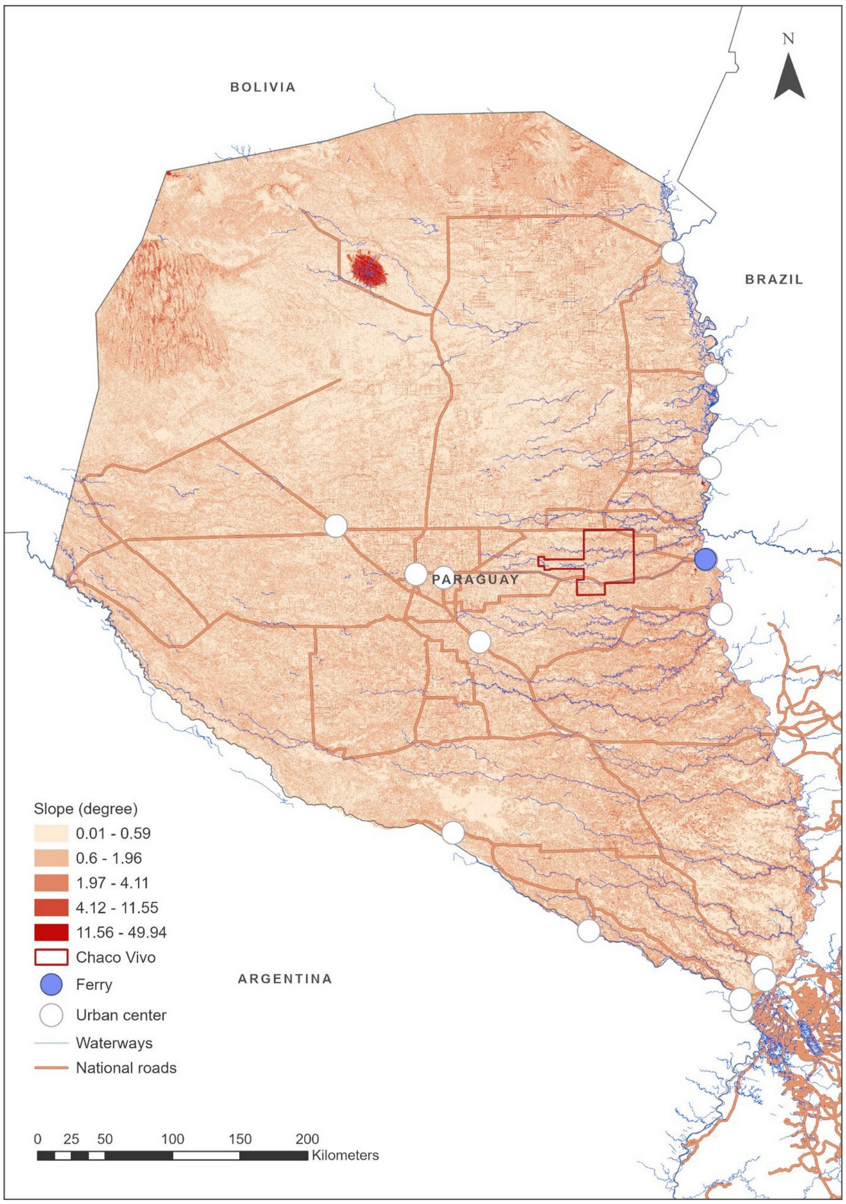

Figure C1. *Slope (degrees) across the Gran Chaco region of Paraguay, derived from digital elevation model data. Slope ranges from 0 to 49.9 degrees, but the overwhelming majority of the study area registers near-zero slope (light peach tones in the graduated colour ramp). The localised area of higher slope in the northwest corresponds to the foothills of the sub-Andean range and falls outside the active conversion zone. The Chaco Vivo property area, marked in the central*

Chaco, lies on terrain with negligible slope. National roads, urban centres, and waterways are shown for reference.

Figure C1 confirms near-zero slope across the central and southern study domain where the proxy parcels and Chaco Vivo property lie; appreciable slope is confined to northwestern foothills outside the study domain.

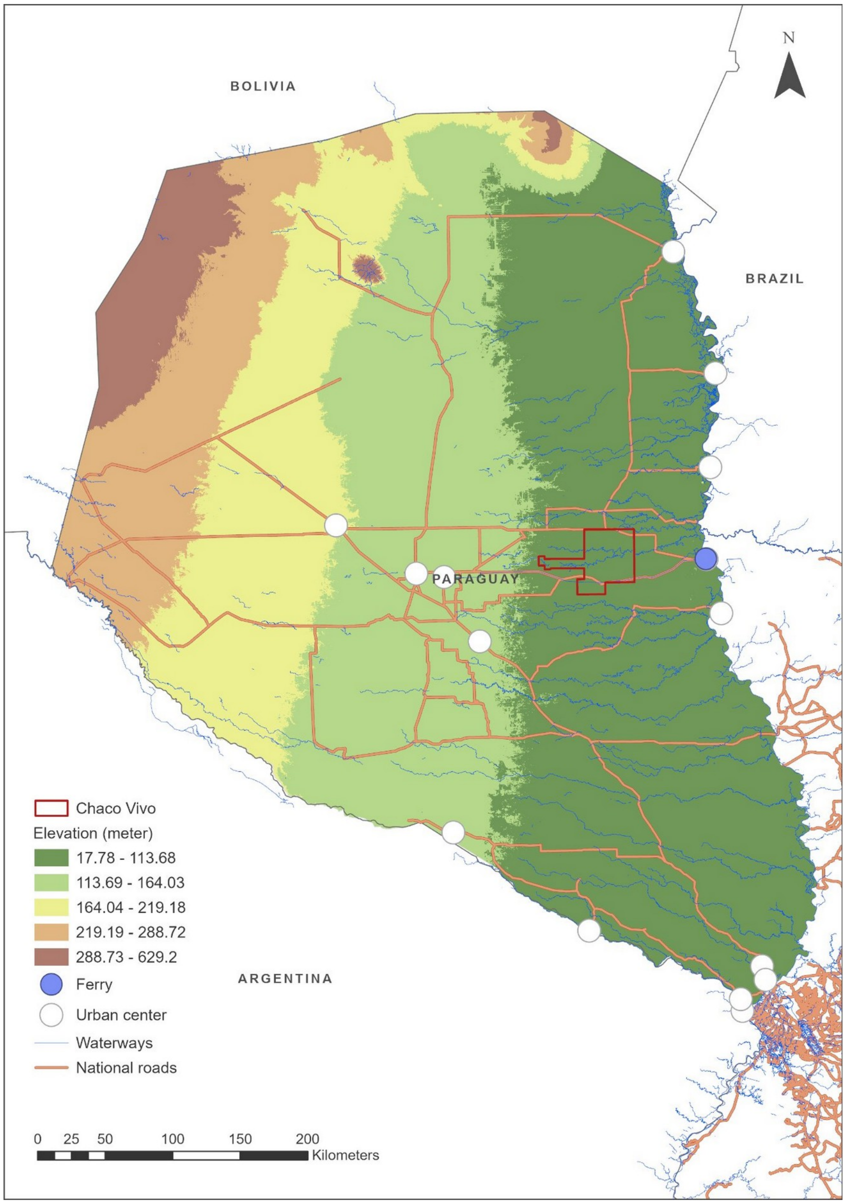

Figure C2. *Elevation (metres above sea level) across the Gran Chaco region of Paraguay, derived from digital elevation model data. Elevation ranges from 17.7 m in the eastern lowlands near the Paraguay River to 629.2 m in the northwestern foothills. The central and southern Chaco, where the study area is located, occupies the 100 to 300 m band (light green to yellow in the graduated colour ramp). The Chaco Vivo property area is situated at approximately 150 to 200 m elevation.*

Figure C2 shows a gentle west-to-east elevation gradient; the study area lies in the 100–300 m band referenced in Section 4.3, within which elevation does not materially constrain clearing timing or intensity.