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Supplementary information

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Subnational mechanisms undermine transnational anti-deforestation policies

In the format provided by the authors and unedited

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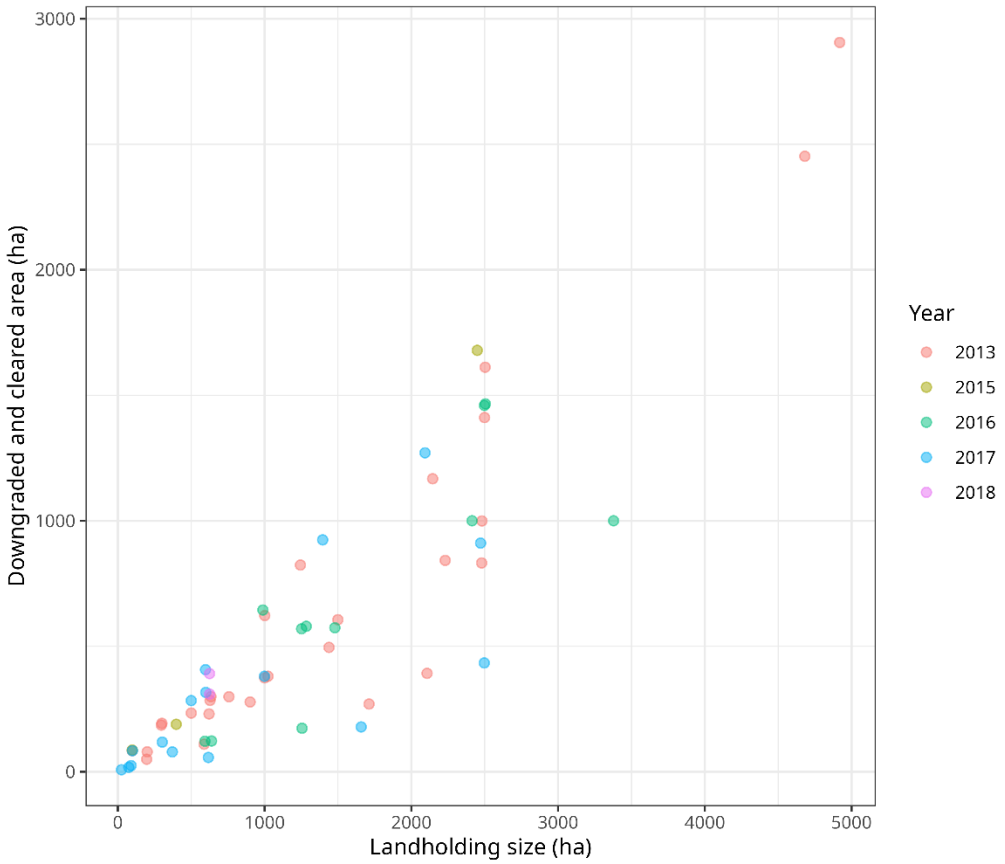

Fig. S1. Downgraded and cleared properties in the Chaco Impenetrable.
The size and the downgraded and cleared area of the 60 landholdings to which the subnational authority, at its discretion, downgraded the protection level and allowed the clearing of almost half, on average, of their landholding area.

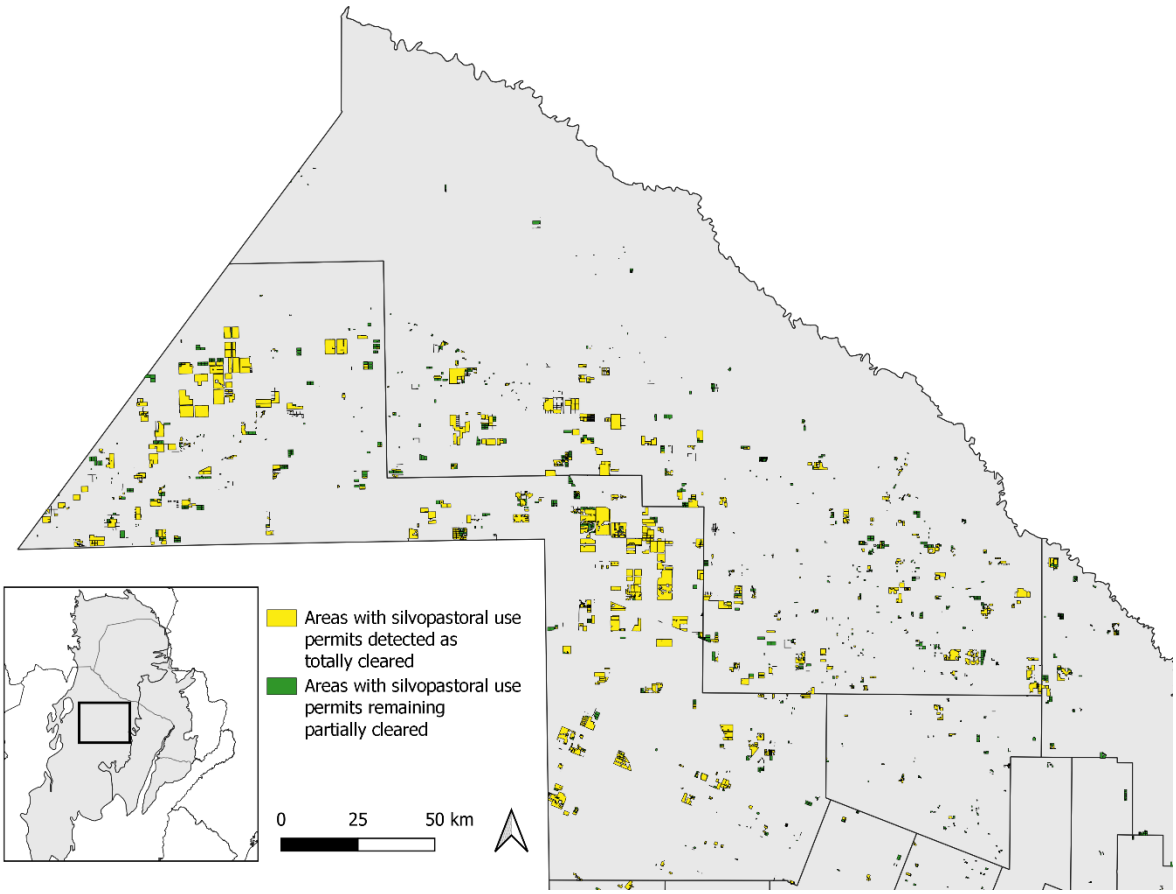

Fig. S2. Time-delayed clearings in the Chaco Impenetrable.

Location of the plots to which the subnational authority granted permits for partial forest clearing and silvopastoral use between 2009 and 2024. A few years after their partial clearing, 64% (72.5 Kha) of silvopastoral plots were detected as totally cleared by the national authority (yellow plots).

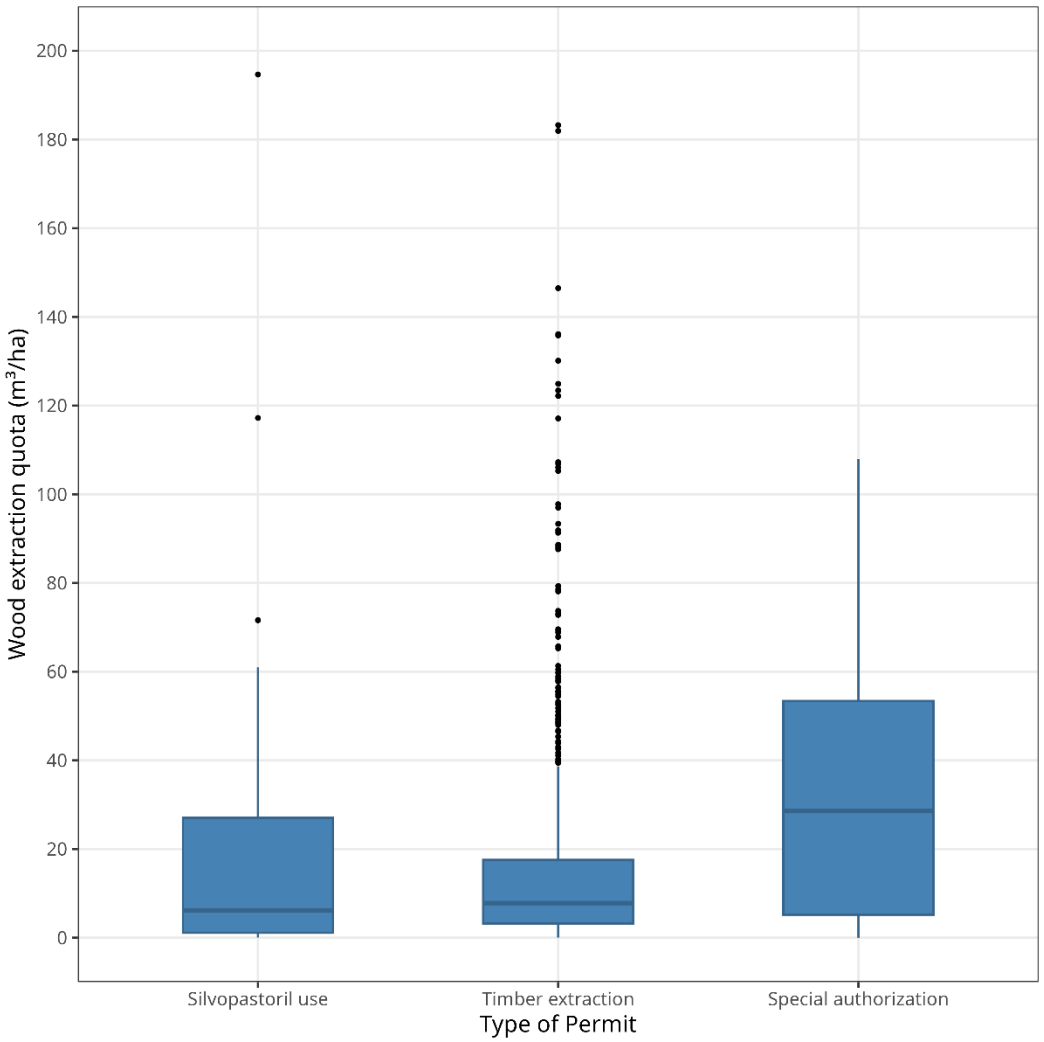

Fig. S3. Overestimation of wood extraction quota in the Chaco Impenetrable.
Distribution of the wood extraction quota granted by the subnational authority through silvopastoral use permits, selective logging permits, and special authorizations to extract wood from illegal clearings. Median wood harvest quotas coincide with wood harvest stocks reported by provincial and national forest inventories; however, wood extraction quotas more than double wood harvest stocks for 16-28% of these wood extraction permits.

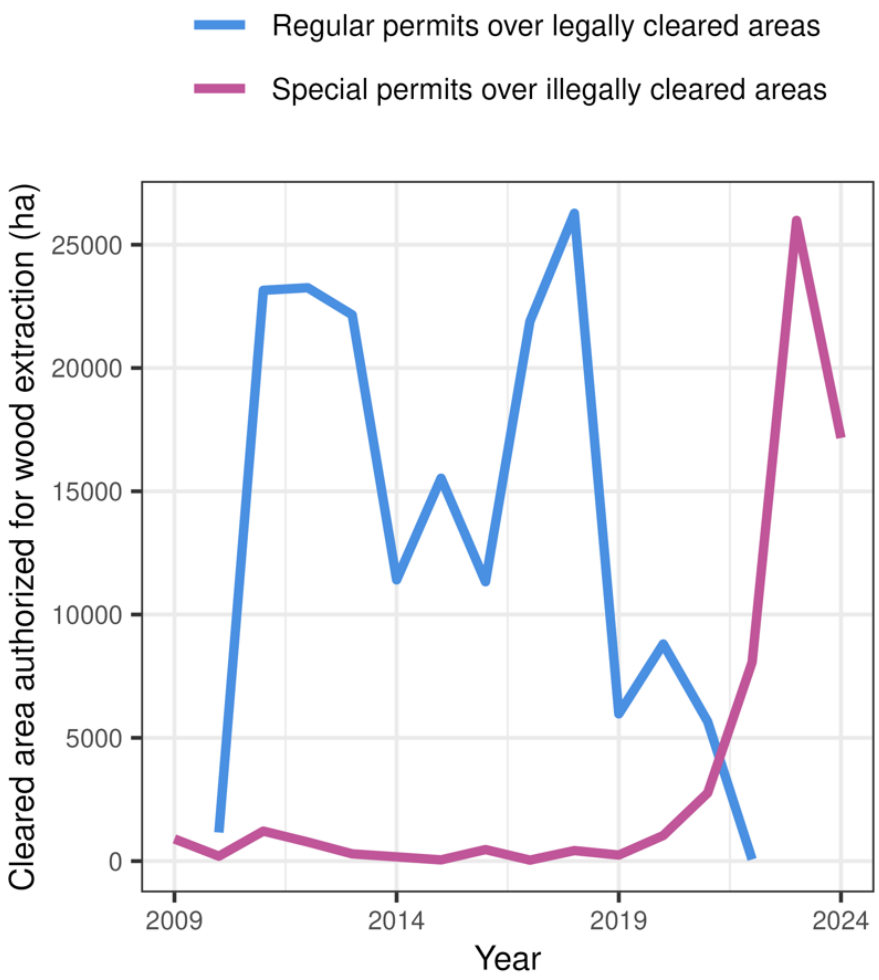

Fig. S4. Wood extraction from illegally cleared areas in the Chaco Impenetrable. Temporal trend in the cleared area to which the subnational authority granted permits for wood extraction. Until 2021, the subnational authority authorized wood extraction mainly from legally cleared areas. In contrast, this authority has systematically and increasingly issued special authorizations to extract wood from illegal clearings in the last four years.

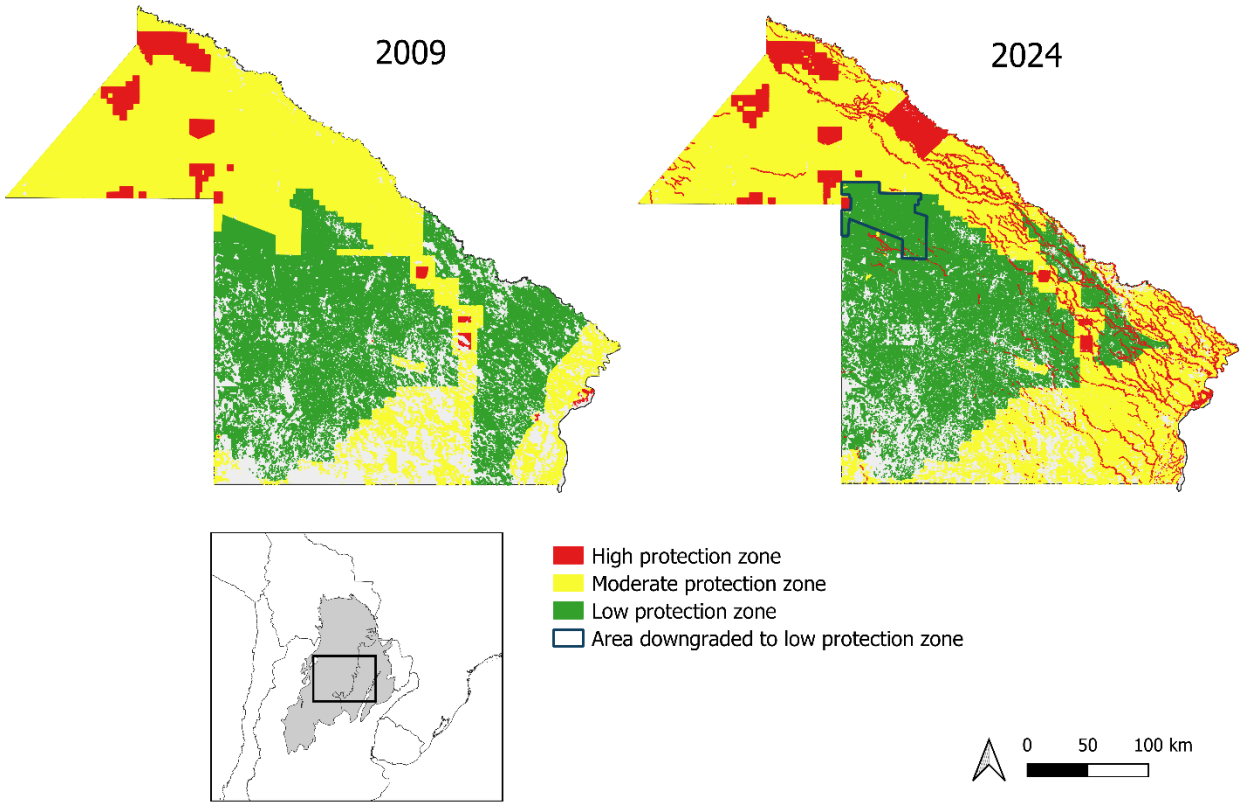

Fig. S5. Regressive updating of the forest zoning plan in the Chaco Impenetrable. Comparison of the initial forest zoning map of the Chaco province sanctioned in 2009 (left) and the updated forest zoning map sanctioned in 2024 (right). As a result of the updating process, the subnational authority downgraded the protection level of 220 Kha of forests of high conservation value and low agricultural suitability in the dry Impenetrable (blue polygon), which was compensated by upgrading the protection level of forests with low conversion pressure in the humid east of the province

Supplementary Text

Sustainability of crop and cattle production in the Impenetrable

To assess the sustainability of crop and cattle production in the Impenetrable forests, we graphically analyzed the temporal evolution of grain yields, harvested area of the main crops, number of cattle heads, and pasture area. Data on grain yields and harvested crop area were obtained from Argentina's Secretariat of Agriculture, Livestock and Fisheries (https://datosestimaciones.magyp.gob.ar/reportes.php?reporte=Estimaciones). The temporal evolution of the number of cattle heads was obtained from the bovine vaccination records of the National Service for Agrifood Health and Quality (https://www.argentina.gob.ar/senasa/programas-sanitarios/cadena-animal/bovinos-y-bubalinos/bovinos-y-bubalinos-produccion-primaria/fiebre-aftosa), and the pasture area was obtained from MapBiomas[54]. Temporal rainfall trends were derived from[55].

In the Impenetrable, crop production shows relatively low yields and high instability. Between 2000 and 2023, average yields were 3,710 kg/ha for maize, 3,334 for sorghum, 2,083 for soybean, and 1,617 for sunflower, implying yield gaps of approximately 45%, 26%, 23%, and 13%, respectively, relative to the national average (fig. S2). Interannual variability is markedly higher, with CVs 3.3 times greater in maize (39.7% vs 12.1%), 2.2 in sorghum (24.2% vs 10.9%), 2.3 in soybean (32.8% vs 14.5%), and 2.0 in sunflower (25.3% vs 12.5%). Although there is a signal of improvement in maize with +102 kg/ha·year ($p = 0.016$), this trend coexists with recent abrupt downturns that erode gains, and no significant changes are detected for soybean, sorghum, or sunflower. Taken together, the combination of low yields and high CV describes a production system with relatively poor productivity and low resilience, highly exposed to climatic shocks and offering little predictability to sustain truly sustainable intensification processes. In addition to rainfall variability, recent studies suggest that reductions in soil organic carbon in the Chaco may also contribute to the decline in crop yields[56].

Between 2002 and 2022, total cattle numbers increased by 53% (1.5×), while the area of pastures expanded by 1,177% (12.8×) (fig. S3). This parallel growth indicates that expansion was achieved primarily by converting additional land to pasture rather than by improving productivity per unit area, as stocking rate (cattle heads per hectare of pasture) declined by 88% over the period. Even though feedlot systems have expanded in the region, no decoupling between the increase in cattle numbers and pasture area was observed, suggesting that production remains extensive. In recent years, cattle numbers have dropped by about 21% from their peak, likely reflecting the severe regional drought (fig. S4), which also affected crop yields as noted previously.

Sustainability of wood production in the Impenetrable

To assess the sustainability of wood extraction in the Impenetrable forests, we graphically compared the temporal evolution of the annual sustainable harvest volume and the annual volume of wood harvested from 2009 to 2024. The annual sustainable harvest volume is the product of the area of undegraded forest and the annual sustainable harvest volume per hectare. To calculate the area of undegraded forest, we subtracted the area of forest lost each year due to land use change[23], fires[57], and degradation[34] from the area of undegraded forest in 2009, according to the 2011 provincial forest inventory[36]. According to[34], the annual sustainable harvest volume per hectare equals 80% of the annual growth volume (1 m^3/ha). We obtained the annual volume of wood harvested from 2009 to 2024 in the Impenetrable by adding up all the primary forest products reported annually in the provincial statistics (https://direcciondebosques.blogspot.com/p/estadisticas.html).

Between 2009 and 2024, an average of 1.11 Mtons of wood were extracted annually from the province of Chaco, of which 57% (0.63 Mtons) came from the Impenetrable. More than half of this wood is used for firewood and charcoal production, and ≈35% to produce extracts of red quebracho tannin. The annual volume of wood extracted from the Impenetrable grew by 60% in the last fifteen years, from 0.45 Mtons in 2009 to 0.73 Mtons in 2024. However, the annual volume of wood that can be harvested sustainably decreased by 45% in the same period, from 0.93 Mtons in 2009 to 0.51 Mtons in 2024. This decrease is due to forest loss from clearing and fires (32 Kha/year) and degradation from logging and cattle ranching (23 Kha/year). As a result, the volume of wood extracted annually from the Impenetrable has exceeded what can be sustainably harvested for the last seven years (2017–2024) (fig. S7).

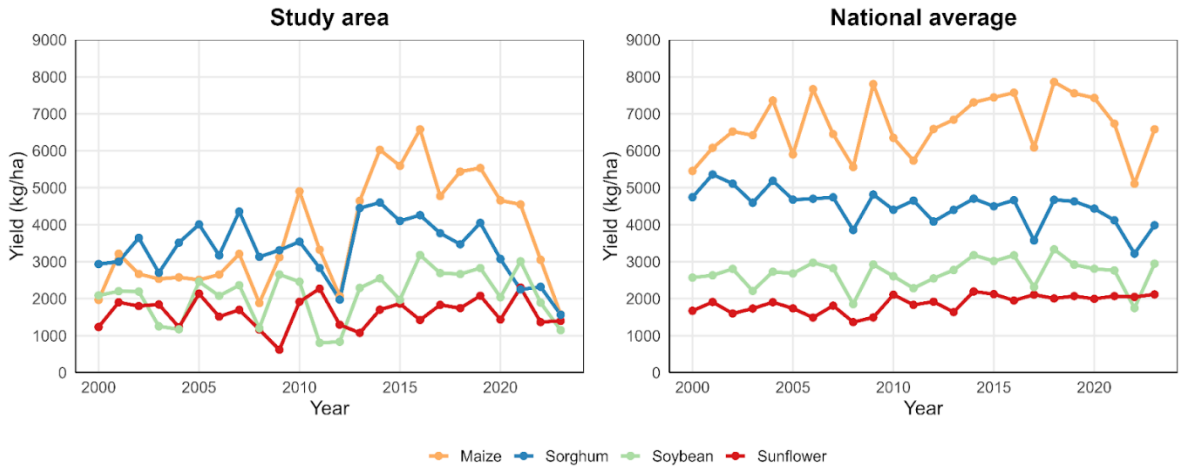

Fig. S6. Sustainability of crop production systems in the Chaco Impenetrable. Temporal trends in the yields of the main crops cultivated in the Impenetrable (left) compared to the national average (right) from 2000 to 2023. Crop yields in the Impenetrable are less stable than the national average and have declined in recent years.

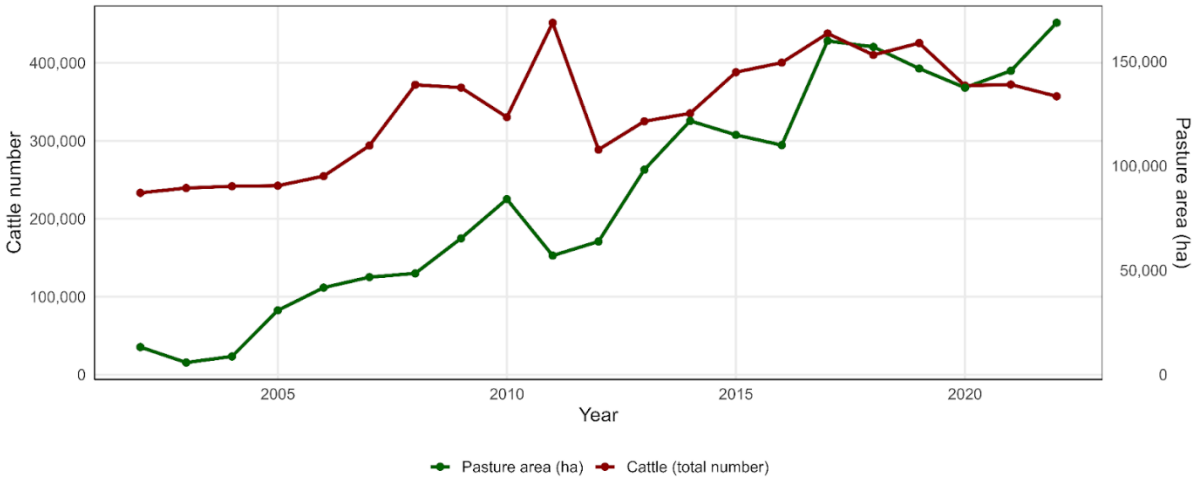

Fig. S7. Sustainability of cattle production systems in the Chaco Impenetrable. Temporal trends in pasture area and number of cattle heads from 2000 to 2022. Stocking rate (cattle heads per hectare of pasture) declined by 88% over the period, indicating declines in productivity per unit of area.

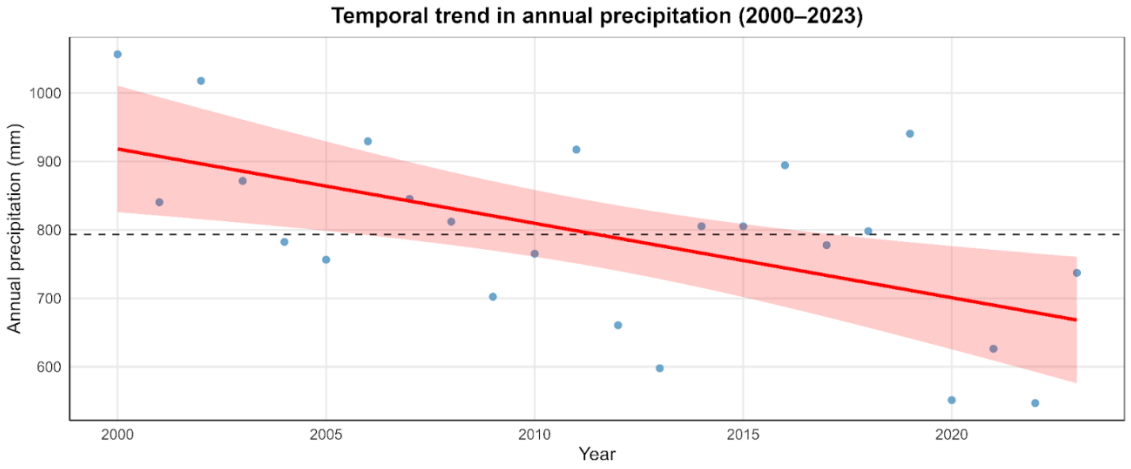

Fig. S8. Declining annual precipitation in the Chaco Impenetrable.
Annual precipitation and linear trend (red line) between 2000 and 2023 for the study area. The dotted horizontal line represents the annual precipitation average for the period.

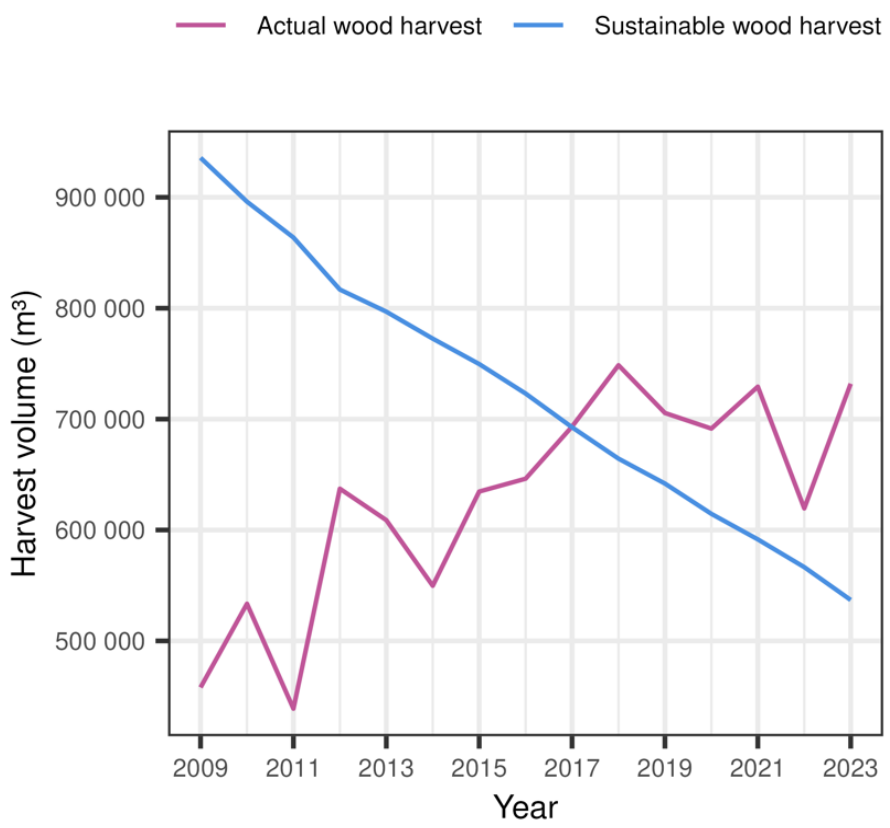

Fig. S9. Sustainability of wood production in the Chaco Impenetrable.
Temporal trends in the volume of wood harvested (purple line) and wood that can be harvested sustainably (blue line) between 2009 and 2023, showing that the former has exceeded the latter for the last seven years.

Table S1. Number, area, and wood volume from forest and land use permits.

Aggregate values obtained by linking and processing data from the official registry of 15,042 forest and land use permits and of 127,632 wood transport guides.

	Logging permits			Silvopastoral use permits			Special authorizations			Total forest clearing	
Year	Number	Area	Wood volume	Number	Area	Wood volume	Number	Area	Wood volume	Permitted area	Cleared area
2010	874	80.444,0	ND	123	21.355,0	ND	8	1.905,0	ND	-	19.369,0
2011	857	66.201,0	ND	117	15.376,0	ND	11	1.464,0	ND	22.698,6	19.369,0
2012	737	53.143,0	ND	86	8.390,0	ND	7	1.045,0	ND	29.880,1	53.572,5
2013	675	61.475,6	ND	25	2.820,3	ND	8	385,0	ND	34.457,3	53.572,5
2014	410	38.157,9	427.109,0	29	2.724,5	17.439,1	9	140,2	16.426,3	8.556,2	19.350,0
2015	651	61.126,0	440.687,4	25	1.714,0	22.048,6	14	195,0	7.698,1	14.505,2	22.797,0
2016	472	43.302,2	551.702,6	62	2.991,4	24.099,1	10	900,4	6.209,9	28.251,0	29.383,0
2017	548	45.357,2	441.655,5	46	4.568,2	23.046,1	7	148,0	32.913,7	25.545,9	43.780,0
2018	243	27.633,1	362.862,9	113	9.910,9	17.522,0	6	61,5	9.933,0	12.627,6	39.774,0
2019	333	33.354,2	262.546,2	46	4.476,3	28.839,5	14	534,7	21.013,9	6.154,1	17.550,0
2020	302	39.633,4	352.903,9	42	4.954,9	31.284,6	20	1.498,5	17.236,9	2.879,6	35.915,0
2021	542	64.093,0	452.726,7	49	5.356,4	47.998,8	41	2.821,1	51.932,3	6.428,1	24.427,0
2022	370	47.896,2	457.237,2	38	5.197,9	32.031,4	77	8.389,6	213.491,8	-	34.152,0
2023	426	61.474,5	435.512,7	40	5.383,6	22.163,1	137	24.156,4	462.520,8	-	57.893,0
2024	220	31.264,6	286.760,3	71	9.164,6	23.732,6	152	25.910,4	577.980,7	-	37.788,0

Table S2. Fines and profits for illegally clearing forests in the Chaco Impenetrable.

Data used to calculate fines for illegal clearing and profits from post-clearing land-uses from 2009 to 2024.

Year	Monthly minimum wage (US$)	Fine amount (US$)	Soy Yield (ton/ha)	Soy price (US$/ton)	Maize yield (ton/ha)	Maize price (US$/ton)	Quebracho Colorado yield (ton/ha)	Quebracho colorado price (US$/ton)
2009	353.08	706.17	1.2	425.72	2	179.91	33	
2010	410.26	820.51	2.8	402.87	3.6	163.38	33	
2011	488.48	976.96	2.5	556.8	4.9	307.86	33	
2012	544.49	1088.99	0.8	577.48	3.4	269.28	33	
2013	579.2	1158.4	0.8	498.01	2.1	295.54	33	
2014	480.97	961.94	2.3	519.42	4.7	217.30	33	
2015	567.49	1134.97	2.6	388.2	6.2	166.29	33	
2016	477.57	955.13	2	422.55	5.6	168.96	33	
2017	539.2	1078.39	3.2	389.72	6.7	158.59	33	
2018	425.85	851.7	2.8	430.32	4.9	179.09	33	80.65
2019	307.26	614.53	2.6	339.81	5.5	171.08	33	66.84
2020	258.78	517.56	2.8	359.17	5.6	143.91	33	91.57
2021	281.97	563.93	2.1	646.8	4.8	305.31	33	97.77
2022	382.32	764.65	3.2	724.09	4.6	344.84	33	100
2023	441.84	883.67	2	595	3	268.14	33	100
2024	266.75	533.5	2	490.22	3.5	197.79	33	100

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