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# Reducing natural vegetation loss in Amazonia critically depends on the formal recognition of indigenous lands

Daniela Prioli Duarte[a,1], Carlos A. Peres[b,c,*,1], Edgar Fernando Cifuentes Perdomo[b,d], Alejandro Guizar-Coutiño[d], Bruce Walker Nelson[a]

[a] National Institute for Amazonian Research (INPA), Manaus, Brazil
[b] School of Environmental Sciences, University of East Anglia, Norwich, UK
[c] Instituto Juruá, Manaus, Amazonas, Brazil
[d] Department of Plant Sciences, University of Cambridge, Cambridge, UK

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ABSTRACT

The Brazilian Amazon contains the world's largest tract of tropical forest, about 22 % of which is within demarcated indigenous territories. Formal governmental recognition of these traditional territories is often a critical deterrent to deforestation, but the relative conservation performance of Indigenous Lands (ILs) under different legal categories and geographic contexts remains poorly understood. We used 30-m resolution Landsat satellite imagery to quantitatively assess the land cover status and annual rates of natural vegetation loss between 1985 and 2020 for 381 indigenous territories amounting to ~115 million hectares. Using a comprehensive set of environmental and socio-economic covariates and a mixed-modelling approach, we found that all stages of formal IL recognition consistently inhibit natural vegetation loss throughout the Brazilian Amazon compared to adjacent unprotected areas. Formal physical demarcation and distance from roads were the main proximate drivers of avoided natural vegetation loss inside ILs. Forest loss associated with road access is substantially curbed by ILs, showing the importance of frontier expansion when assessing indigenous reserve performance in counteracting natural vegetation loss. Because loss of natural forest and savannah areas associated with agribusiness frontiers and infrastructure projects are likely to intensify, the importance of ecosystem services provided by ILs is expected to increase across the Brazilian Amazon. Cultural profile and human density exerted no impacts on IL effectiveness in precluding natural vegetation loss. Given widespread encroachment of timber extraction and agribusiness, formal recognition of indigenous territories is a critical factor in decelerating primary habitat conversion across the Amazon.

## 1. Introduction

The world's attention once again turns to Amazonian forests as awareness of climate change and the biodiversity crisis escalates. Over the past few years, there has been a rebound in annual deforestation rates across the Amazon. The Brazilian Institute for Space Research (INPE) estimates that 27,800 km$^2$ were deforested across the Brazilian Amazon from August 2019 to July 2022 (INPE, 2019), representing the highest cumulative rate over 3 years and a 5.7-fold increase since the same period a decade earlier.

The Brazilian "Legal Amazon" spans 5,217,423 km$^2$, ~83 % of which is within a forest domain, amounting to the largest tropical forest region controlled by a single country. The remainder land area includes parts of two other biomes, the Cerrado scrub savannahs (15 %) and the Pantanal wetlands (1 %). Currently, there are 424 Amazonian Indigenous Lands (ILs) recognized by the Brazilian government. Altogether, these amount to 1,153,444 km$^2$ (~22 % of the Brazilian Legal Amazon) and are inhabited by 180 recognized ethnic groups and at least 28 confirmed isolated groups (FUNAI, 2020). As of 2020, about 28 % of all ILs in the Brazilian Amazon had yet to complete their physical demarcation process, two of which had awaited their presidential ratification decree since 1996. Moreover, approximately 85 % of all ILs across the Brazilian Amazon regularly confront encroachment by land grabbers and illegal logging which degrade the forest structure (Walker et al., 2020) and

* Corresponding author at: School of Environmental Sciences, University of East Anglia, Norwich, UK.
*E-mail address:* C.Peres@uea.ac.uk (C.A. Peres).
[1] These two authors contributed equally to this work.

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natural resource capital essential to their legitimate occupants (FUNAI, 2020; RRI - Rights and Resources Initiative, 2015).

Indigenous Lands (ILs) are fundamentally established to safeguard the rights and livelihoods of indigenous peoples, but that recognition takes various forms in different countries. Typically, formal recognition consolidates indigenous peoples' rights to remain in their territory and use its resources for subsistence (FAO and FILAC, 2021). Several studies have shown that recognizing the right to territorial claims by indigenous peoples and traditional communities (IPTCs) is a promising avenue for de facto conservation in low-governance tropical forests (Garnett et al., 2018; Fa et al., 2020; Blackman et al., 2017). Formal sanctioning of indigenous land rights is likely critically important in terms of protecting forests and meeting commitments to mitigate climate change. Garnett et al. (2018) show that lands managed by indigenous peoples represent over a quarter of the world's land surface, comprising some 40 % of all protected areas. Additionally, the world's remaining intact forests declined by only 4.9 % within indigenous areas between 2000 and 2016, in contrast to 11.2 % elsewhere (Fa et al., 2020). Furthermore, high-integrity forests across the tropics tend to be concentrated within the overlap between protected areas and indigenous territories (Sze et al., 2022), reinforcing the importance of recognizing contributions from indigenous governance to forest conservation.

The association between IL recognition and forest retention is widespread throughout Latin America, where indigenous peoples occupy ~404 million hectares, over 80 % of which is forested (Garnett et al., 2018). Nelson and Chomitz (2011) used matching techniques to control for differences in deforestation pressure and found that indigenous reserves in Latin America significantly reduce forest fire incidence compared to unprotected areas. Across the pan-Amazon, ILs substantially reduce deforestation and forest degradation in Peru (Schleicher et al., 2017; Blackman et al., 2017) and Bolivia (Boillat et al., 2022). In Colombia, communal lands effectively protect forests even in remote sites where state governance and institutional capacity are weak (Bonilla-Mejía and Higuera-Mendieta, 2019).

The conservation performance of Amazonian ILs has been generally regarded to be highly positive (e.g.; Baragwanath and Bayi, 2020; Begotti and Peres, 2020; Herrera et al., 2019; Nepstad et al., 2006; Nolte et al., 2013; Ricketts et al., 2010; Soares-Filho et al., 2010). Overall cumulative forest loss within all demarcated ILs across the Brazilian Amazon was <2 % as of 2020, whereas the total area outside ILs experienced ~20 % of deforestation (ISA, 2020). Losses in carbon stocks from vegetation clearing inside ILs have been considerably lower than those outside, although forest degradation has become a growing concern within indigenous territories (Walker et al., 2020). This is consistent with earlier studies showing that ILs deter deforestation even compared to state-managed strictly protected areas (Nepstad et al., 2006), although these authors found no effect of indigenous population density, nor time since contact, on the extent to which ILs inhibit deforestation.

Previous studies have also shown that the IL inhibitory effect on deforestation was particularly effective along the so-called "arc of deforestation" of Amazonia. In this region, deforestation pressure is exacerbated by high road density, land-grabbing, logging, and agricultural expansion (Santos et al., 2022). Considering forest cover loss throughout Brazilian Amazonia over the 2001–2010 period, ILs confronted the highest levels of deforestation pressure, but performed best among all protected area categories in avoiding deforestation (Nolte et al., 2013). In contrast, patterns of deforestation avoidance among protected areas were variable over the 2009–2014 period, when strictly protected areas outperformed indigenous lands in terms of proportional forest area spared (Jusys, 2018). However, positive spillover effects of ILs have been detected in increasing deforestation rates in neighbouring areas within the Amazonian "arc of deforestation" (Pfaff et al., 2014).

Evidence to date on how ILs avoid deforestation compares to other protected areas is still inconclusive. Within Brazil's legal and administrative framework, ILs fall outside the legislative domain of, nor are they governed by, the Brazilian National System of Conservation Areas (SNUC). In contrast with strictly protected nature reserves, ILs have no legal restrictions on land use and forest resource exploitation, as long as these activities are carried out by indigenous residents for their own benefit (Constitution of Brazil, 1988). Thus, the degree to which indigenous territories will hold their long-term baseline condition remains controversial among conservation biologists (e.g. Peres, 1994; Peres and Terborgh, 1995; Redford, 1992). Since 2019, the performance of ILs in deterring deforestation has been severely undermined by the deliberate dismantling and weakening of environmental regulations by the current Brazilian administration, leading to widespread land grabbing within traditional territories in areas of economic interest (Conceição et al., 2021).

These studies have, however, overlooked the additional protection effect of the different stages of formal land demarcation on deforestation avoidance, and the ethnic component of IL occupants on such effect. These stages are here defined as the major legal milestones in the formal IL recognition process and official approval by the federal National Indian Foundation (FUNAI), following Law Decree 1775/1996 (Fig. S1.1). Each step provides a new layer of territorial security and brings indigenous occupants closer to ensuring control over their own territory, and the maintenance of traditional modes of subsistence, often characterized by a more harmonious relationship with natural ecosystems.

Instead, most studies have either treated the indigenous domain as a single static condition or consider only fully ratified ILs. BenYishay et al. (2017) examined how deforestation responded to *de jure* demarcation of 106 indigenous communities in the Brazilian Amazon during the 1982–2010 period with territorial demarcation as a covariate. Using long-term changes in the maximum annual NDVI vegetation index as a proxy for deforestation within 4 km × 4 km cells of AVHRR and MODIS satellite sensors, this study found no evidence that formalizing Indigenous Land rights, or supporting surveillance and community enforcement, affected the extent to which deforestation could be suppressed. However, AVHRR data cannot readily detect tropical deforestation, and MODIS data, although an improvement over AVHRR, is of much lower spatial resolution than is Landsat. MODIS-based data represent an early warning system to support surveillance, but this sensor is not recommended to adequately quantify deforestation because of large off-nadir view angles, cloud contamination within the large MODIS pixels, and failure to detect many forest clearings at the MODIS sub-pixel scale (Diniz et al., 2015).Previous studies have also lumped the complexity of Amazonian indigenous ethnicities into a single social group. This neglects the diversity of indigenous cultural identities and their inherent understanding of resource management, economic activities, and territorial enforcement. Adequate governmental enforcement of the laws protecting indigenous territories from squatters, illegal resource extraction by third-parties, and other forms of encroachment is typically unfeasible. We therefore hypothesize that part of the variance in IL effectiveness in curbing deforestation could be explained by ethno-cultural factors, inferred by the group of speakers of any language trunk, which is potentially reflected on territorial governance and active enforcement of legal restrictions on outside drivers of encroachment.

Here, we address this problem within the framework of two policy-relevant questions: (1) how does formal recognition of Indigenous Land rights affects rates of natural vegetation loss within indigenous territories compared to unprotected areas elsewhere? and (2) what are the environmental and socio-economic predictors of the effectiveness of vegetation loss avoidance? To answer these questions, we analyzed a comprehensive dataset on the time-series of demarcation events of 381 officially recognized ILs across the entire Legal Brazilian Amazon region, along with ~1400 population census data points, ethnic-linguistic information from all territories, and different covariates representing physical accessibility. Annual land cover data were derived from Landsat images classified by the MapBiomas project (www.mapbiomas.org). We further examined observed step-changes in deforestation avoidance throughout the legal stages of the official IL ratification process using both linear and broken-stick regression models. This allowed us to investigate a long-term time series (1985–2020) based on reasonable spatial resolution (30 m), providing a more refined understanding of patterns of natural vegetation loss in response to the sanctioned demarcation of indigenous territories.

## 2. Material and methods

### 2.1. Overview

To assess the role of formal demarcation of ILs in deterring natural vegetation loss across the Brazilian Legal Amazon, we compiled data for 381 ILs on the basis of five datasets: (1) IL geographic location and size; (2) administrative acts defining the year of *de jure* implementation for each judicial stage in the demarcation process; (3) natural vegetation loss within each IL polygon, within its respective external 10-km buffer, and elsewhere in Brazilian Amazonia; (4) population size and language trunks spoken; (5) human population density; (6) a geographic network of federal and state roads, both paved and unpaved, and (7) mean travel time to the nearest population center. We then intersected these datasets to examine the conservation performance of ILs considering natural vegetation loss over time and in relation to both their buffer zones and comparable areas elsewhere in the Amazon.

### 2.2. Study area

For this study, we included the entire ~5.2 million km$^2$ Legal Brazilian Amazon, which is comprised of nine Brazilian states. Our sample consists of 381 officially recognized ILs as of 2019, for which geographic polygons are available from FUNAI (Funai, 2020). In total, these

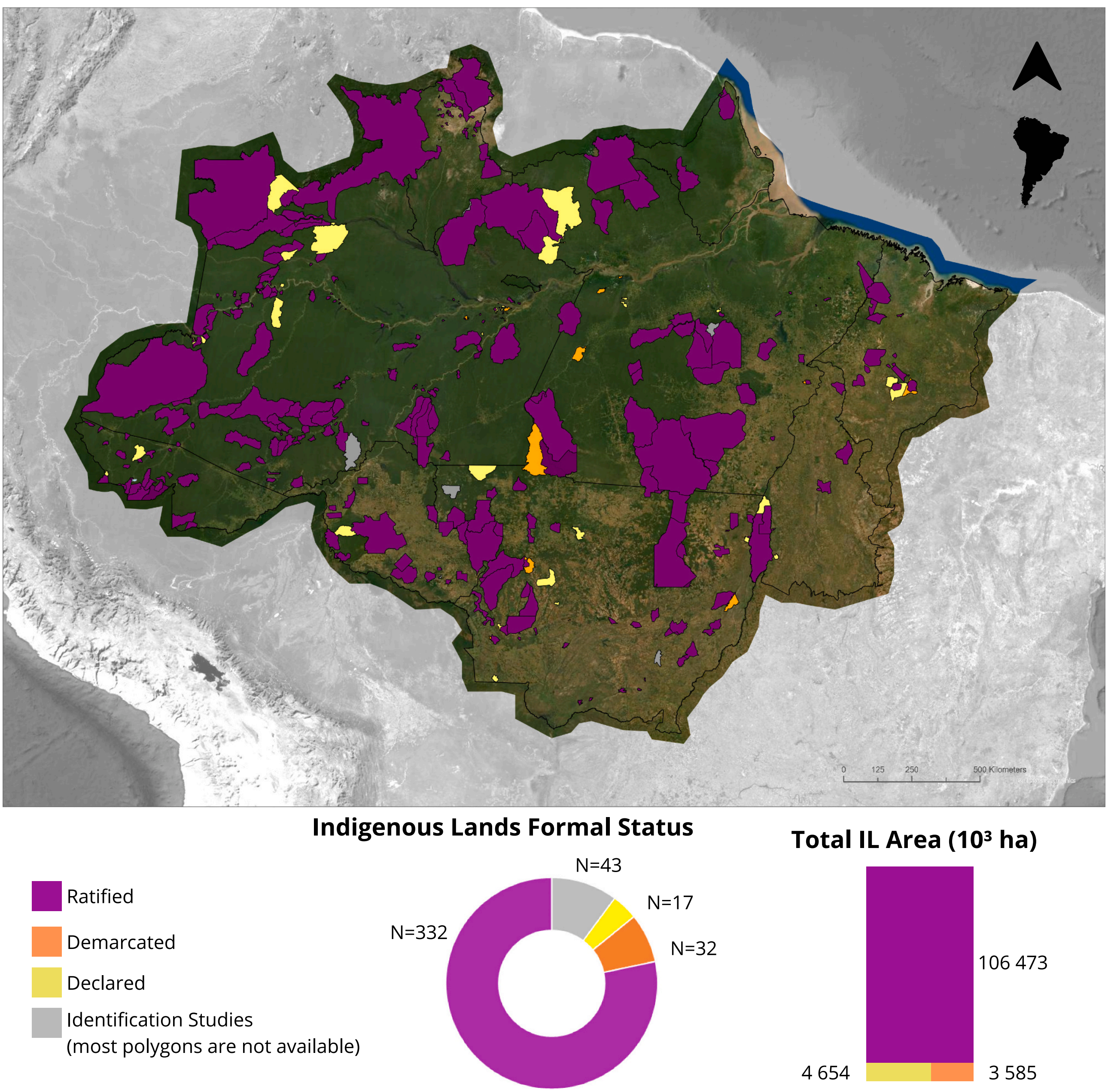


**Fig. 1.** Formal stages of Indigenous Land demarcation across the Legal Brazilian Amazon. Map of Indigenous Lands (ILs) showing the formal stages of demarcation reached for 381 ILs for which boundary polygons are available. Most of the 43 ILs at Stage 1 of the administrative process have not been physically delimited nor have an official polygon and therefore are not shown.

represent almost 90 % of all 424 existing ILs throughout the Brazilian Amazon.

### 2.3. IL legal landmarks

Formal recognition of ILs in Brazil must observe sequential administrative steps and procedures as defined by specific legislation (Decree 1775 of 1996; see Supplementary Information, Fig. S1.1). Data on the formalization process for each IL and the year when each administrative act was sanctioned were acquired from FUNAI (www.funai.gov.br) and Instituto Socioambiental (www.institutosocioambiental.org). For analytical purposes, we considered the formal demarcation process to follow four successive judicial stages — (i) Demarcation studies; (ii) Declaration of Boundaries; (iii) Physical Demarcation; and (iv) Final Ratification (see Supplementary Information 1) — which reflect the status of all ILs across the Legal Brazilian Amazon (Fig. 1).

The calendar year of an official recognition milestone and the time elapsed since that milestone varies across ILs. To account for time between each yearly observation of the deforestation avoidance ratio of an IL ($t_{obs}$) and the milestone implementation year of a given demarcation type, we used the official completion year of the demarcation stage as time zero ($t_0$). Our variable “Time (yrs) from/to demarcation” is therefore $t_{obs} - t_0$ and can take positive or negative values if $t_0$ occurred before or after $t_{obs}$, respectively. We then applied this separately for each of the last three demarcation stages (Declaration of Boundaries; Physical Demarcation; and Final Ratification).

### 2.4. Natural vegetation loss avoidance metric

To quantify vegetation cover conversion on an annual basis, 30-m pixels that had been previously classified in terms of land use – land cover (LULC), were extracted from MapBiomas collection version 6.0 (MapBiomas, 2022) for each IL and its respective 10-km external buffer area. We selected this buffer size to match the maximum legally mandated distance threshold sanctioned by law for all protected areas in Brazil (Almeida-Rocha and Peres, 2021). MapBiomas 6.0 is a 30-m resolution Landsat-derived thematic raster brick comprising 35 annual time steps (1985–2020) of LULC data for the entire Brazilian Legal Amazon region. This product is derived from an annually aggregated temporal mosaic of Landsat pixels, which eliminates most clouds and cloud shadows within each year. ILs and their adjacent buffer areas examined here amounted to 1,937,591 km$^2$, or 37.1 % the entire Legal Amazon region. In addition, in a separate analysis we use a multivariate matching approach to compare rates of vegetation loss between 1.04 million 1-km$^2$ pixels within ILs and 2.13 million pixels spanning unprotected areas anywhere outside ILs (see below).

The total area of each LULC class was extracted for each IL, its respective buffer area, and a large selection of random points across the Brazilian Amazon (see below and Matching Analysis in Supplementary Information 2) for each of the 36 years, using the R platform (R Core Team, 2019) and the *Raster* package (Hijmans and van Etten, 2012). We consolidated the MapBiomas land cover classification into a smaller number of classes to quantify the annual total area of natural vegetation that was either retained or converted into an alternative land-cover (Supplementary Table S1.2). Natural vegetation included forest, savannahs, mangroves and other non-forest formations, while anthropogenic land cover (cropland, livestock pasture, infrastructure and mining) were defined as natural vegetation loss. Annual rates of natural vegetation loss were expressed as proportions of the total polygon area and calculated for both the IL polygon and its external buffer area. For this, we created a geospatial rule that prevented reversals following deforestation, meaning that once a pixel is deforested, it retains that nonforest class.

IL buffer zones include all other land uses or protection levels, but exclude any area contained within any neighbouring IL. Legally demarcated ILs in the Brazilian Amazon do not overlap with other federal and state-managed protected areas. To quantify the performance of each IL in terms of avoiding natural vegetation loss for each year between 1985 and 2020, we used the annual fractional loss of natural vegetation in the 10-km external buffer area surrounding an IL relative to the annual fraction lost inside the IL. To be sure, we also tested that this metric was not temporally biased due to a general increase in annual deforestation rates over time in the external buffers. Had we found that our avoidance metric increased with external cumulative deforestation, that could be due to a null model of increasing expression of any innate avoidance capacity later in time (i.e., after demarcation) and lower expression of avoidance capacity in earlier years. However, we found no relationship between cumulative deforestation within buffer areas and our metric of deforestation avoidance (Fig. S1.3). We also addressed how the temporal progress in IL status (declaration, demarcation and ratification) covaries with distance to the nearest agricultural frontier (Fig. S1.4) to verify the possibility of unobserved, time-varying confounds, which could indicate a displacement in land-use change, rather than a protection effect.

### 2.5. Matching analysis

Matching refers to a suite of synthetic control methods that can derive counterfactual causal inferences from observational data by pairing sets of treatment and control groups that are as similar as possible (Stuart, 2010), thereby measuring the empirical distribution of potential confounders. Matching covariates are often related to the outcome of interest, in this case, rates of natural vegetation loss. We therefore used a matching approach to identify sets of 1-km$^2$ grid cells, within which 30-m Landsat pixels had been aggregated, anywhere across the wider matrix of formally ‘unprotected’ areas within the Legal Brazilian Amazon region. Matched cells could thus be selected from any area within the same major baseline vegetation type but outside both ILs and other state-managed protected areas. These matched grid cells were similar to those inside ILs in observable covariates that could exert confounding effects on forest loss, including distance to the nearest road, human population density, and travel time to the nearest population center, thereby ensuring proper comparability between ILs and any unprotected area elsewhere. Further details on the matching analysis are available in Supplementary Information 2.

### 2.6. Population data

Data on total population sizes occupying each IL were retrieved from Instituto Socioambiental (ISA, 2020), FUNAI (2020) and the last official decadal census available for the entire Brazilian territory (IBGE – Instituto Brasileiro de Geografia e Estatística, 2010).

### 2.7. Ethnicity ordination

Ethnic group refers to any grouping that distinguishes itself from others by cultural criteria and symbology, such as language, beliefs, norms and history (Gabbert, 2006). FUNAI data for ILs include the ethnic and genealogical linguistic features for occupants of each IL, which can be subdivided into 55 language trunks (or families) which differentiate through either relative isolation or systems of conscious identity preservation. Information on operational linguistic trunks inside each indigenous territory was assembled from the FUNAI open database and used as a proxy of IL cultural heritage, hereafter termed “ethnicity”. A Principal Coordinates Analysis (PCoA) was then performed to summarize the original assembly of languages spoken within the boundaries of each IL, given the composition (presence/absence) of the 55 language trunks known in the Amazon region. The ordination score of each IL along the first PCoA axis was used as a covariate representing this cultural variable (Fig. S1.5). Our rationale was that (1) different ethnic and cultural backgrounds may have different value systems that are reflected on patterns of land use and integration into the market economy, (2) the composition of different languages within each IL forms a gradient of IL objects in cultural space, and (3) this gradient may therefore partly explain socio-cultural profiles that either inhibit or facilitate the conservation performance of any IL.

### 2.8. Road accessibility

Physical accessibility was used as a covariate in both the matching analysis and a fixed effect in the mixed-effects model. This was represented by the distance between any pixel and the nearest major road. We acquired geographic information on paved and unpaved roads managed at the state or federal level, based on the Brazilian Ministry of Infrastructure (www.infraestrutura.gov.br). This official road map was overlaid with the IL map to obtain the nearest Euclidian distance between any point along the reserve perimeter and the nearest road. Roads that were either immediately adjacent to or intersected any given IL boundary were assigned a distance of zero.

### 2.9. Data analysis

#### 2.9.1. Segmented regression analysis

A time series of annual mean aggregated avoided vegetation loss for each IL, and the time before or after each of the three demarcation milestones (Declaration of Boundaries, Physical Demarcation and Final Ratification) were used to fit a three-segment broken-stick regression model with two unknown transition points using the R platform (R Core Team, 2019) and the *mcp* package (Lindeløv, 2020). We also used analysis of variance (ANOVA) to test whether any increment in mean vegetation loss avoidance observed for each IL during the 5-yr post-demarcation period was significantly different from that during the 5-yr pre-demarcation period.

#### 2.9.2. Model building

We used the R platform (R Core Team, 2019) and the *spaMM* package (Rousset and Ferdy, 2014) to perform generalized linear mixed-effects models (GLMMs) examining IL performance in avoiding natural vegetation loss. The response variable was a single observation per IL of its cumulative vegetation loss avoidance up to 2020. We selected as explanatory variables (fixed effects) (1) time (yrs) since demarcation, for which we used the final ratification date, (2) reserve area, (3) human population density, (4) ethnicity ordination score, and (5) distance to nearest road. Covariates and response variables were standardized prior to modelling. IL identity was considered a random effect in the GLMMs. We dealt with both the spatial and temporal autocorrelation structure by (a) fitting an autoregressive term (AR1) to correct for serial correlation and control for inter-annual variation in natural vegetation loss, both within and outside the ILs; and (b) adding a covariance structure (Matern) for the IL spatial data, for which correlation decays exponentially with distance between ILs. Visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity or normality.

## 3. Results

### 3.1. Natural vegetation loss of indigenous lands

For our purposes, the formal process of demarcation was disaggregated into four legal stages: (i) Studies of Demarcation; (ii) Declaration of Limits; (iii) Physical Demarcation; and (iv) Ratification (See Supplementary Fig. S1.1). The status of all ILs across the Legal Brazilian Amazon according to these successive stages as of 2020 is presented in Fig. 1. At present, a total of 332 ILs (77.5 %) achieved the final stage of demarcation, while at least 43 (10 %) are still awaiting the first stage of FUNAI approval. Because these 43 early-stage ILs still lack any physically demarcated boundary polygon, they could not be included in our analysis.

For the entire Legal Amazon region, most of the total acreage of indigenous territories was formally designated during the 1990–2000 period. During our period of analysis (1985–2020), the total official area of all ILs combined increased 60-fold (Fig. 2).

During our period of analysis (1985–2020), 10 km-buffer zones around ILs on average lost between 4.85 (year 1985) and 13 times (year 2000) more natural vegetation than their respective ILs ($N = 381$, Fig. 2). Cumulative natural vegetation loss within an external buffer area was as high as 78 %, such as in the Tadarimana Reserve of Mato Grosso, southeastern Amazon. Despite this extremely heavy external deforestation pressure, this reserve still retained >97 % of forest cover within its boundaries.

### 3.2. Chronosequence of avoided natural vegetation loss

Our temporal analysis confirms the contribution of all three demarcation milestones to avoiding vegetation loss within ILs across the Brazilian Amazon. Broken-stick linear models were set to identify the three best fitted segments and two breakpoints. A period of enhanced contribution to avoiding annual vegetation loss is manifested by the upward slope of the central segment in all three cases (Fig. 3). The best-fit central segment always started within 5 years before and ended within 10 years after the demarcation milestone. Final ratification was particularly effective when considering the mean difference of intercepts between the first (mean = 0.07 ± 0.05) and the third segments (mean = 0.24 ± 0.11), resulting in two stepped plateaus.

ANOVA comparisons of annual rates of mean avoided vegetation loss within the 5-year period before (mean = 0.10 ± 0.09), compared to the 5-year period after (mean = 0.27 ± 0.17) formal IL designation, also show a significant aggregate contribution of all three stages of demarcation, which are completed with the final ratification milestone (mean difference = 0.17, $p < 0.001$; Fig. 4). Achieving final ratification on average prevented the loss of an extra 1810 km$^2$ of forest and savannah vegetation in the Brazilian Legal Amazon each year, across all 332 ILs that had obtained this legal status. These additional conservation gains are equivalent to 30 % of the total annual deforestation across the Brazilian Amazon over the 2009–2018 decade. A further 140 km$^2$ in annually avoided deforestation could be added to that amount in the future, if the 49 ILs that still lack ratification had been granted this status by Presidential Decree.

### 3.3. Spatial analysis of avoided vegetation loss

We found that vegetation loss within 10-km buffer areas outside ILs was highly uneven across the region, with most forest loss detected within or near the rapidly expanding agricultural frontier of southern and southeastern Amazonia (Fig. 5A). This was mirrored by the matching analysis in which IL deforestation rates are compared to random control points elsewhere in the Amazon sharing the same profile of deforestation-risk covariates (Fig. 5B). The states along the 'Arc of Deforestation' show the highest levels of cumulative forest loss within both external buffers and matched control points. ILs also follow this trend with most deforestation concentrated in the agricultural frontier states of Mato Grosso (mean = 7.7 % ± 1.4 %, $N = 65$), Maranhão (6.6 % ± 1.6 %, $N = 17$) and Pará (5.9 % ± 1.6 %, $N = 53$). On the other hand, the most intact ILs are located in Amapá (0.2 % ± 0.2 %, $N = 6$) and Amazonas (0.8 % ± 0.3 %, $N = 136$), which have been exposed to much lower deforestation pressure and retain the highest proportions of forest cover.

### 3.4. Drivers of IL conservation performance

Our mixed-effects model coefficients revealed the impact of physical accessibility, represented by the distance between any given IL boundary and the nearest paved and unpaved road, as an important predictor of IL performance in terms of deforestation avoidance (Fig. 6), in which a negative coefficient (z = −3.92) indicates road access as a factor in

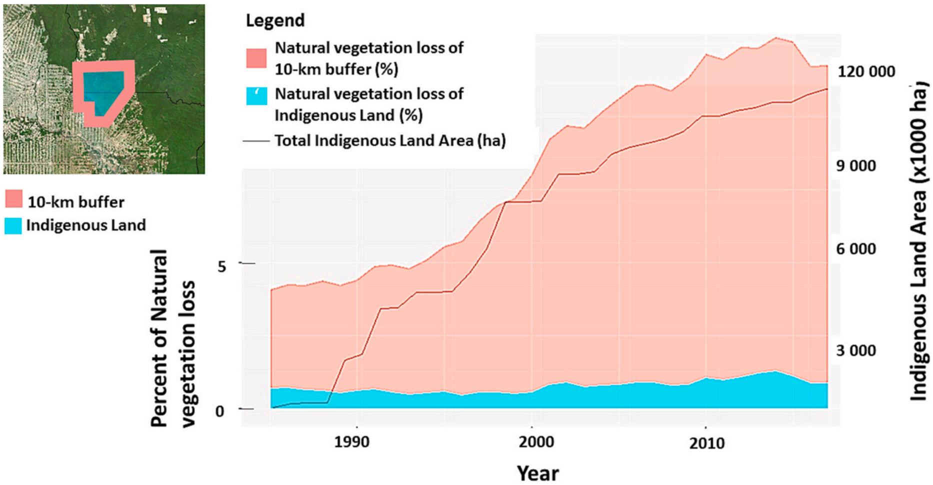


**Fig. 2.** Demarcated Indigenous Lands and cumulative natural vegetation loss between 1985 and 2020. Cumulative proportion of natural vegetation area lost within IL boundaries (blue) compared to the respective proportional loss within their external 10-km buffer areas (red), between 1985 and 2020. Black line shows changes in the overall IL demarcated area across the Brazilian Amazon over the same period. Inset map shows an example of the 10-km wide external buffer outside the IL boundaries. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

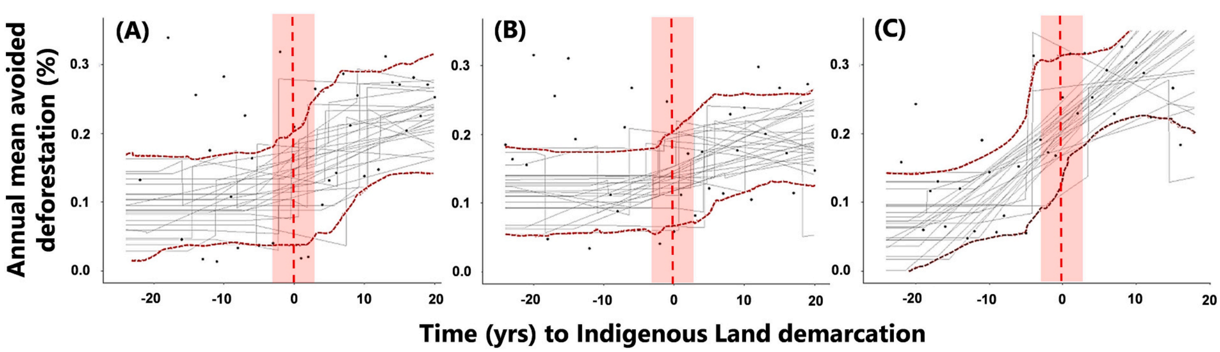


**Fig. 3.** Segmented regression analysis of average annual avoided deforestation within ILs. Broken-stick linear regression models with two break points, fitted to the annual means of avoided vegetation loss for all Amazonian Indigenous Lands, and the amount of time both before and after each of the three demarcation milestones: (A) Declaration of Boundaries, (B) Physical Demarcation, and (C) Final Ratification. Black dots indicate average annual avoided deforestation within all ILs, whereas black lines indicate individual IL trajectories, in terms of avoided deforestation. Dark red dotted lines indicate 2.5 % and 97.5 % CI regions. Vertical red dotted line and pink shading indicate year of demarcation and the 3-year period before and after demarcation. All demarcated ILs are included in the analysis. The annual metric of deforestation avoidance for each IL is its incremental annual natural forest/savannah loss within an IL relative to the same value for the buffer area immediately outside. Although most of these ILs have completed all four ratification stages, time intervals between milestones are highly variable. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

forest loss (Table 1). IL demarcation, in terms of the amount of time (yrs) since the final ratification of IL boundaries was the second most significant predictor of avoided vegetation loss within ILs ($z = 2.24$). Estimates for other variables (reserve area and ethnicity) were uninformative in explaining IL effectiveness in protecting forest cover.

## 4. Discussion

Our models have clearly shown that the *de jure* Indigenous Land demarcation process since the earliest stages, but particularly after the final ratification, consistently accounts for greater effectiveness in avoiding vegetation loss, compared to both the pre-landmark periods and unprotected areas elsewhere. These findings build on previous evidence that ILs are effective in precluding vegetation loss in relation to non-IL landscapes whether these are in immediately adjacent areas or elsewhere. For now, ILs appear to be at least as effective as other protected area categories in slowing down location-specific deforestation and forest degradation both in Brazil (Baragwanath and Bayi, 2020; Begotti and Peres, 2020; Herrera et al., 2019; Nepstad et al., 2006; Nolte et al., 2013; Ricketts et al., 2010; Soares-Filho et al., 2010; Carranza et al., 2014; Nolte et al., 2013) and other Amazonian countries (Peru: Nelson and Chomitz, 2011; Blackman et al., 2017; Schleicher et al., 2017; Bolivia: Boillat et al., 2022; Colombia: Bonilla-Mejía and Higuera-Mendieta, 2019). We further provide counterfactual evidence in relation to prior studies that inferred that IL demarcation was no more effective in avoiding deforestation than unprotected areas in Brazil (Pfaff et al., 2014), and that the IL declaration of boundaries status provides no additional deterrence to vegetation loss across the Brazilian Amazon (BenYishay et al., 2017). Our matching analysis, which transcends the immediate neighbourhood of any IL, is additional confirmation of the protection effect exerted by properly sanctioned indigenous territories. Compared to ILs, cumulative deforestation rates in matched grid cells were higher in regions experiencing lower deforestation, but much higher within buffer areas in regions experiencing higher deforestation. This can be interpreted as further evidence of the deterrence effect of ILs in areas of elevated external encroachment, if not "leakage" or "spill-over" effects (Ewers and Rodrigues, 2008).

More importantly, we demonstrate that all successive stages of official recognition of Amazonian Indigenous Lands significantly reduced natural vegetation loss. However, the magnitude of this effect varied across the different administrative stages in what often amounts to a prolonged drawn-out process. To our knowledge, this is the first study that unravels the performance of the consecutive stages of the indigenous territory demarcation process in avoiding natural vegetation loss. Previous studies have treated physically demarcated ILs as a single static condition, or only considered fully ratified territories.

Baragwanath and Bayi (2020) considered the effects of indigenous land demarcation on deforestation before and after property rights are

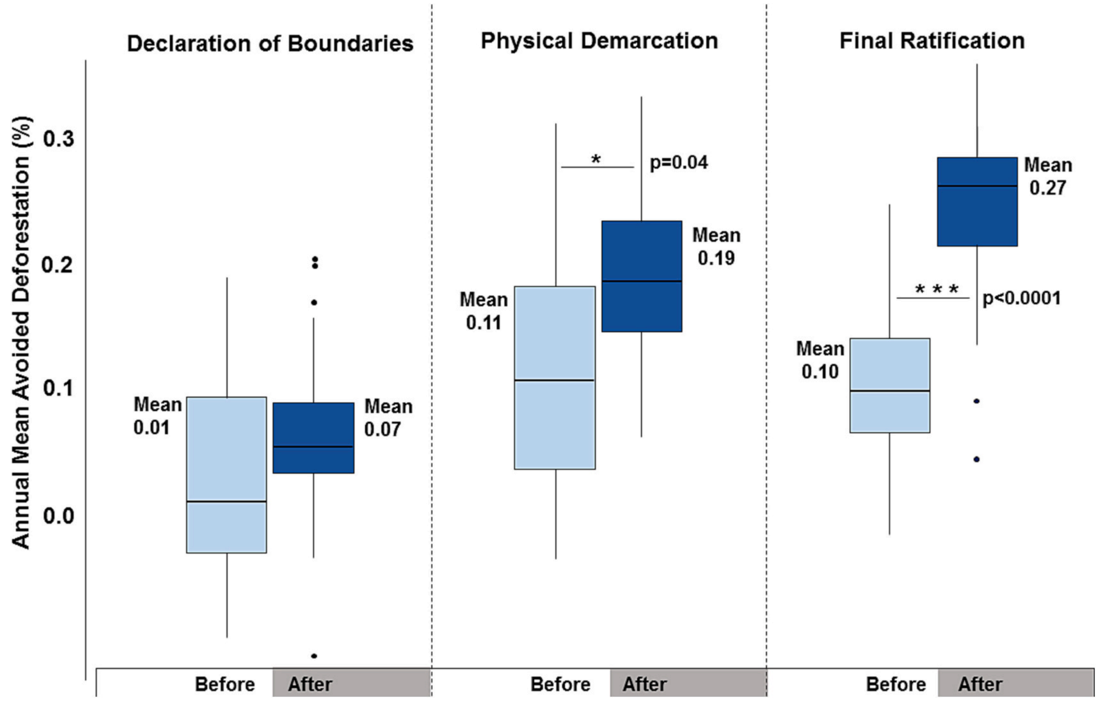


**Fig. 4.** Mean avoided deforestation across ILs before and after their legal recognition milestones. ANOVA results and *p*-values are shown for mean differences in annual avoided deforestation between periods prior to (light blue) and after each demarcation stage (dark blue). All demarcated ILs are included in the analyses. The annual metric of deforestation avoidance for each IL is its incremental annual forest loss within an IL relative to the same value for the buffer area outside. Although most of these ILs have completed all four ratification stages, time intervals between them are highly variable. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

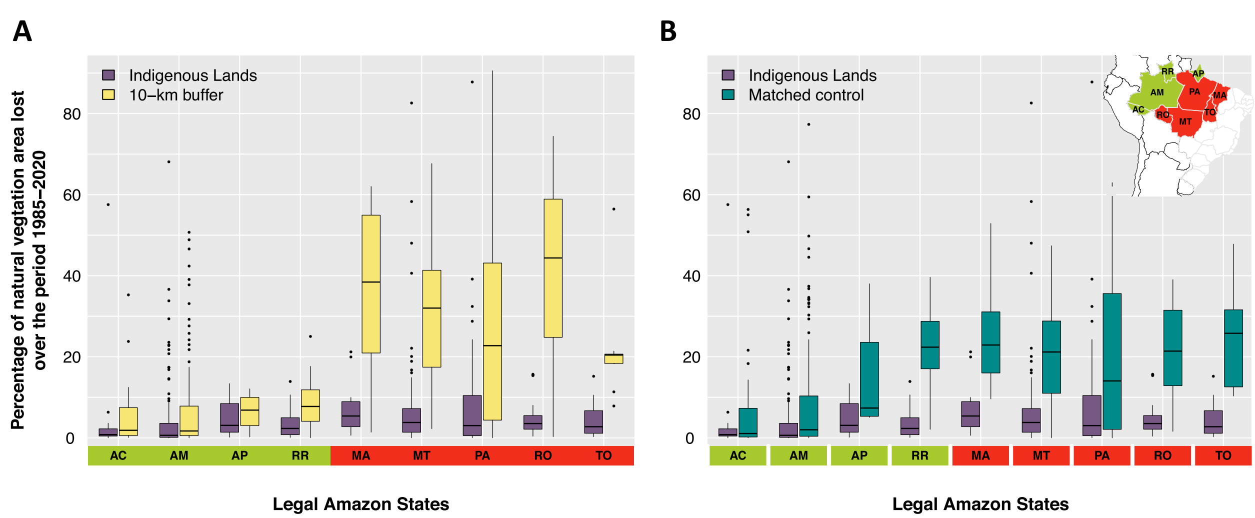


**Fig. 5.** Cumulative deforestation rates within ILs and elsewhere across all states in Brazilian Amazonia, including (A) buffer areas adjacent to ILs, and (B) matched control points in unprotected areas anywhere in the Legal Brazilian Amazon using three key covariates (see text). Relative amount of forest loss as of 2020 within official ILs and their respective buffer areas by state: AC = Acre ($N = 32$), AM = Amazonas ($N = 136$), AP = Amapá ($N = 6$), RR = Roraima ($N = 34$), MA = Maranhão ($N = 19$), MT = Mato Grosso ($N = 68$), PA = Pará ($N = 53$), RO = Rondônia ($N = 20$), and TO = Tocantins ($N = 12$). States shaded in red are those most affected by the so-called 'Arc of Deforestation' region of Brazilian Amazonia. States shaded in green have experienced much lower deforestation rates. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

obtained in the Brazilian Amazon, using the orthogonality of the timing of full IL ratification. Our study uses a similar methodology, but goes further in showing the additional effects of each of the four stages of formal recognition. Our findings also substantially add to previous studies by including all physically demarcated ILs throughout the Brazilian Amazon and employing higher resolution (30 m) analysis over a 36-yr period.

Early stages of demarcation (Declaration of Boundaries and Physical Demarcation) establish official IL boundaries and, crucially, provide financial resources to remove and compensate any non-indigenous occupants within each territory. This occurs well before the Final Ratification and grants native Amazonians full and exclusive access to their own territories and natural resources, leading to positive consequences in resolving inter-ethnic conflicts over land tenure. A subsequent presidential ratification decree rubber-stamps the last administrative step in the overall demarcation process, providing definitive legal status to any


**Fig. 6.** Proximate drivers of IL conservation performance in terms of avoided vegetation loss. Estimated coefficients and 95 % confidence intervals of explanatory variables in mixed-effects models for IL avoidance of natural vegetation loss. For this model we used the incremental annual forest loss within an IL relative to the same value for its adjacent buffer area outside. The year of IL Final Ratification was considered as the main demarcation milestone used as a fixed effect in the model. IL identity was used as a categorical random effect.

**Table 1**
Parameter estimates and fit statistic from model outputs explaining the effectiveness of natural vegetation loss avoidance.

| | Fixed effects | | | | |
|---|---|---|---|---|---|
| | Time (yrs) since ratification | IL area | Population density | Ethnicity | Distance to roads |
| Coefficient | 0.138 | 0.007 | 0.014 | −0.019 | −0.286 |
| SE | 0.061 | 0.054 | 0.031 | 0.063 | 0.073 |
| Lower 95th | 0.080 | −0.044 | −0.016 | −0.078 | −0.355 |
| Upper 95th | 0.196 | 0.059 | 0.044 | 0.041 | −0.216 |
| Z | 2.244 | 0.132 | 0.439 | −0.300 | −3.919 |
| p | <0.0001 | – | – | – | <0.0001 |

IL.

The procedure through which the Brazilian Government formally demarcates indigenous homelands is under the aegis of FUNAI (Fundação Nacional do Indio), which follows a complex and frequently controversial process. Although the 1988 Brazilian Constitution states that indigenous territorial rights precede any official land recognition, the unfolding of the demarcation process is often susceptible to the political whims of the federal executive branch in bargaining for support from state and municipal governments and a conservative National Congress dominated by the powerful agribusiness lobby (the *ruralista* backbenchers). IL demarcation is therefore a political bargaining chip that can delay the process for decades, with detrimental consequences for both the land rights of indigenous peoples and the conservation of natural ecosystems. Approximately 62 % of all indigenous territorial recognition in the Brazilian Amazon occurred between 1990 and 2010, which was fueled by benign socio-ethnic policy and wider public opinion. Only 9 % of all new Indigenous Land demarcation took place during the decade since 2010 and 588 territorial claims remain on hold (ISA, 2020). None of these claims have been ratified by the current (Bolsonaro) administration, although this may change once again from 2023 under the newly elected (Lula) government. In regions undergoing frontier expansion, indigenous property rights often collide with mining (especially illegal gold-mining), land grabbers ("*grileiros*") and large-scale logging interests, all of which often result in violent conflicts, land expropriation and infectious disease transmission (Villén-Pérez et al., 2020; Begotti and Peres, 2020).

With regard to drivers of deforestation in the Brazilian Amazon, we can confirm earlier evidence that physical accessibility is a major proximate determinant of deforestation and forest degradation (Laurance et al., 2002; Nepstad et al., 2001; Soares-Filho et al., 2004). Our findings show that forest loss associated with road access is likely to be curbed within fully sanctioned ILs, and that agricultural, logging and mining frontier expansion matters when assessing the performance of indigenous territories in counteracting forest and cerrado scrubland conversion.Most studies on protected area effectiveness have been largely restricted to geophysical and economic variables, particularly concerning governance, topography, and proxies of anthropogenic disturbance, including roads, timber extraction and mining. However, incorporating the influence of socio-cultural factors can be particularly important in understanding drivers of natural vegetation loss and forest degradation (Wilshusen et al., 2002). Begotti and Peres (2020), Nepstad et al. (2006) and de Marques et al. (2016) considered human population density in their conservation performance analyses of indigenous and nature reserves. Our modelling approach, which incorporated ethnic composition, reserve size and human population density, corroborates their findings in that increasingly higher population density within ILs does not appear to affect their environmental services in terms of avoided vegetation loss. Similarly, gradients in ethnic background, inferred by linguistic composition of ILs, were uninformative in explaining reserve performance, even though key variables such as time since first contact with non-indigenous groups, governance structure, land management techniques and alternative income opportunities can vary widely across Amazonian ethnicities. This is in line with the notion that, despite the diversity of indigenous peoples and their modes of social organization, a common philosophy emerges regarding their relationship with their territories and elements therein (Cárdenas Marín and Vallejos Roa, 2022). Escobar (2015) highlights that in exercising autonomy, native peoples transcend issues of territorial defense and natural resources. This could explain the tenacity with which many native populations in the American tropics fight to defend their territories, their concept of development, and relationship with nature.

This is particularly noteworthy since conventional preservationist worldviews on natural resource use often question the long-term sustainability of traditional indigenous practices under contexts of high population growth and modern market integration (e.g. Peres and Terborgh, 1995; Redford, 1992). This notion has often led to a failure to integrate local indigenous populations into protected area management (McSweeney, 2005; Robinson, 2011). We therefore reinforce previous findings showing that the effects of population growth, ethnic-linguistic composition and economic integration on the conservation effectiveness of indigenous territories is not as straightforward as many conservationists would have it.

In any case, Amazonian ILs will continue to be very susceptible to external drivers of degradation. Since the onset of Jair Bolsonaro's administration in January 2019, forest degradation within Amazonian ILs, including deforestation, illegal logging and wildfires, have increased 140 %, and the most exposed ILs succumbed to 23,639 ha of new deforestation between August 2020 and July 2021 (Oviedo et al., 2021). Our results show heavier losses of natural vegetation cover inside ILs, their external buffer areas, and control points elsewhere in growing portions of Amazonia most exposed to the agribusiness frontier, compared to more remote ILs, for example, in western and northern Brazilian Amazonia. These findings build on previous studies showing that ILs are disproportionately located in areas of higher deforestation pressure, thereby further enhancing their services in potentially inhibiting natural vegetation loss (Nelson and Chomitz, 2011; Nolte et al., 2013; Pfaff et al., 2014).

These results are imperative within the current political scenario in Brazil. With the changing winds of Brazil's national geopolitics and an economic downturn, the extent to which Amazonian forests are allocated to native Amazonians is often seen as excessive. Governmental efforts to turn the economy around frequently follow an agribusiness-oriented agenda, including a promise to suspend any further ratification of Indigenous Lands (Ferrante and Fearnside, 2019), thereby continuing the declining trend in numbers of officially decreed Indigenous Lands since the 1988 Constitutional Reform (Begotti and Peres, 2020). Traditional people's territories are often viewed by central governments as too large to be relegated to “unproductive” lands. This agenda goes further by (1) downsizing or de-listing other Protected Area categories; (2) proposing to downgrade existing environmental legislation; and (3) calling for large infrastructure projects, including mining, dams and highways, even within ILs and other protected areas (Tollefson, 2018). The latter are known catalysts of deforestation, thereby suppressing previous hard-won achievements in controlling deforestation across the Amazon (Rochedo et al., 2018). This is consistent with both the hike in overall deforestation during the Bolsonaro years (2019–2022) and the substantial increase in the size of individual deforestation polygons (Trancoso, 2021). At least 19,057 ha of new deforestation was induced by illegal goldmining in five ILs in 2021 alone (MapBiomas, 2021). In the Kayapó and the Yanomami reserves, 11,542 and 1556 ha were respectively cleared by >15,000 gold-miners (FUNAI, 2020) who continue to threaten not only the integrity of those reserves, but also indigenous health and safety. Following the 2022 national elections in Brazil, expectations run high for indigenous land rights as the newly elected president (Lula da Silva) created a new Ministry of Indigenous Peoples in the federal government, which for the first time in Brazilian history will be led by a native Amazonian. However, a hostile National Congress majority can still sanction a series of bills to legally pardon land-grabbing and allow mining by third-parties within ILs, and downgrade or eliminate environmental licensing of infrastructure projects, setting the stage for a difficult administration in the 2023–2026 period concerning environmental and indigenous affairs (Peres et al., 2022).

## 5. Conclusions

We present unequivocal evidence that, compared to unprotected areas elsewhere, the sanctioning of *de jure* recognition of Amazonian indigenous territories accounts for substantial effectiveness in precluding deforestation, even if IL management protocols fail to be implemented. Notably, we show that the downstream benefits for forest conservation can be observed since the earliest stages of formal recognition. Our findings provide a timely reminder of the nature conservation benefits of officially recognized indigenous territories, which have increasingly become the last refugia of endemic species in otherwise highly deforested regions. This may ideally unfold as three main politically feasible contributions in (1) safeguarding indigenous rights prior to the conclusion of pending demarcation workflows; (2) weakening ongoing legislative initiatives that limit or prohibit the IL recognition process; and (3) strengthening government and civil-society institutions that support native people's territorial rights. Finally, in line with a number of empirical assessments indicating that tropical deforestation and unsustainable depletion of natural resources are associated with frail institutions and law enforcement, we advocate that strengthening government agencies responsible for IL surveillance (in this case, FUNAI and Brazil's Ministry of Environment) is vital to both restrain predatory overexploitation of Amerindian territories and enhance their long-term conservation benefits.

## CRediT authorship contribution statement

**Daniela Prioli Duarte:** Data compilation, Data curation, Original draft preparation, Visualization. **Carlos A. Peres:** Conceptualization, Methodology, Supervision, Data analysis, Writing, Reviewing & Editing. **Edgar Fernando Cifuentes**: Data curation, Data analysis. **Alejandro Guizar-Coutiño**: Data analysis: **Bruce W. Nelson:** Supervision, Reviewing and Editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2023.109936.

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