Yanai, A.M., M.A. Isaac Júnior, J.N. da Silva, M.A. dos Santos Junior, P.M.L.A. Graça & P.M. Fearnside. 2025. **Modeling the impact of planned highways on deforestation and illegal land occupation in a critical area of Brazilian Amazonia: The Trans-Purus region.** *Regional Environmental Change* 25: art. 120. https://doi.org/10.1007/s10113-025-02459-w

ISSN: 1436-3798
DOI: 10.1007/s10113-025-02459-w

Title: Modeling the impact of planned highways on deforestation and illegal land occupation in a critical area of Brazilian Amazonia: The Trans-Purus region

Authors: Aurora Miho Yanai[1*], Marcos Antonio Isaac Júnior[1], Jonathas Nunes da Silva[2,3], Marcelo Augusto dos Santos Junior[4], Paulo Maurício Lima de Alencastro Graça[1], Philip Martin Fearnside[1]

Affiliations:
[1]Department of Environmental Dynamics, National Institute for Research in Amazonia (INPA); Av. André Araújo n° 2936, CEP 69067-375, Manaus, Amazonas, Brazil.
[2]Department of Chemistry, Federal University of Amazonas (UFAM); Av. General Rodrigo Octávio n° 6200, CEP 69080-900, Manaus, Amazonas, Brazil.
[3]Center for Analysis, Research and Technological Innovation Foundation (FUCAPI); Av. Governador Danilo de Matos Areosa n° 381, CEP 69075-351, Manaus, Amazonas, Brazil.
[4]National Institute for Space Research (INPE), Av. dos Astronautas n° 1758, CEP 12227-010, São José dos Campos, São Paulo, Brazil.

*Corresponding author. Email: yanai@inpa.gov.br

Email address: yanai@inpa.gov.br; maisaacjunior@gmail.com; jonathas.water@gmail.com; brasa.bio@gmail.com; pmlag@inpa.gov.br; pmfearn@inpa.gov.br

Abstract:
Deforestation in Brazilian Amazon impacts ecosystem services, affects the Amazonian population, and contributes to global warming. Public policies promoting highway construction pose a major threat to a critical area of undesignated public forests in Brazilian Amazonia: the Trans-Purus region – a vast forest area west of the Purus River in Amazonas state. The forest in this region is largely intact, as its inaccessibility by road makes it less attractive to land grabbers, but it could become a new deforestation hotspot if planned highways are built. We projected the potential impact of planned highways on deforestation and the advance of illegal land occupation under a business-as-usual scenario in the Trans-Purus region and its surrounding areas, including the BR-319 highway region to the east, the Humaitá and Labrea areas to the south, the region Juruá area to the west and the Manaus influence region to the north. A baseline scenario (without highways) was also simulated for comparison. The business-as-usual scenario showed a reduction of 15% (57,818 km^2) of remaining forest from 2022 to 2070. The increase in deforestation (17,470 km^2) between the business-as-usual and baseline scenarios was greater in the Trans-Purus region than in any of the four surrounding regions we simulated. In the Trans-Purus region, the mean annual deforestation increased from 23 km^2 to 483 km^2 with the highways, and undesignated public forests showed substantial deforestation, demonstrating the role of highways in facilitating the access of actors from Brazil's "arc of deforestation." The magnitude of potential impacts implies the need to reconsider government policies on Amazon development that rely on highway projects.

Keywords: land grabbing; public forests; cattle-ranching frontier; landholdings; undesignated public forests; environmental modeling.

1. Introduction

Deforestation in Brazil's Amazon forest is of paramount concern due to its impact on both biodiversity and climate. Depending on the course of deforestation in the coming decades, the resulting greenhouse gas emissions could be critical in pushing the global climate system over a tipping point, unleashing a "runaway greenhouse" where global temperatures rise uncontrollably, ending in a "Hothouse Earth" with mean global temperature at least 4-5 °C above the preindustrial mean (Steffen et al. 2018). Strong biogeophysical feedbacks, including Amazon forest dieback, would release so much carbon that eliminating all direct anthropogenic emissions (such as fossil fuels and deforestation) would be insufficient to contain global warming (Fearnside 2020a; Fearnside and Silva 2023).

Emissions from Amazon deforestation are added to those from forest degradation from logging, fire, edge effects, dry season lengthening and the increasing frequency of extreme droughts and temperatures (Bottino et al. 2024; Lapola et al. 2023; Marengo et al. 2018; Matricardi et al. 2020). Continued deforestation also risks crossing fast-approaching tipping points for the Amazon forest in terms of the maximum tolerable percentage of forest loss (Ferrante et al. 2021a; Lovejoy and Nobre 2018; Nobre et al. 2016a), dry-season length (Sampaio et al. 2018) and temperature (Trisos et al. 2020). A recent study based on multiple stressors (Flores et al. 2024) calculated that much forest could collapse by 2050 in the region that is the subject of the present study – the vast "Trans-Purus" region in Brazil's state of Amazonas.

Loss of the Amazon rainforest would eliminate the water recycling performed by the forest, which is a climatic function that is vital to Brazil and neighboring countries. Water recycled by the forest is transported as water vapor to areas such as southern and southeastern Brazil by winds known as "flying rivers" (Arraut et al. 2012; Fearnside 2004, 2015). The percentage of the annual rainfall in the La Plata River basin, which includes Brazil's state of São Paulo, has been variously estimated at 16% (Yang and Dominguez 2019), 18-23% (Zemp et al. 2014), 23% (Martinez and Dominguez 2014) and 70% (van der Ent et al. 2010). Even the lowest of these estimates implies catastrophic consequences if the Amazon forest is lost or significantly reduced. In a major drought in 2014, greater São Paulo (the World's fourth largest city) came close to running out of water even for drinking, and another catastrophic drought hit this part of Brazil in 2021 (Fearnside 2021; Nobre et al. 2016b). The climate in southeastern Brazil has changed (and is projected to worsen), and there is no longer leeway for losing any of the contribution of water from the Amazon forest.

Brazil's Amazon forest is at a critical juncture because government plans for highway infrastructure would open roughly half of what remains of this forest to the entry of deforesters (Fearnside 2022). The planned "reconstruction" of the BR-319 (Manaus-Porto Velho) highway would connect the relatively intact central Amazon around Manaus to the notorious "AMACRO" deforestation hotspot surrounding the borders between the states of Amazonas, Acre and Rondônia. "AMACRO" (the initials of these three states) refers to the 58,117-km^2 area of an agribusiness and cattle ranching development project encompassing 32 municipalities located in southern Amazonas, eastern Acre and northwestern Rondônia. Historically, this region has been characterized by high rates of deforestation, forest degradation and land grabbing (Chave et al. 2024; SUDAM, 2021). Deforesters from this area would gain access not only to the BR-319 highway route itself (the sole focus of the still-unapproved environmental impact assessment) but also to all areas already connected to Manaus by road, including the forest in northern Amazonia up to Brazil's border with Venezuela, and to the vast intact forest area in western Amazonia that would be opened by planned roads connecting to BR-319. These roads would open the Trans-Purus region to the west of the Purus River that runs parallel to BR-319 (Fearnside and Graça 2006; Fearnside et al. 2020). This area has an enormous stock of carbon (Nogueira et al. 2015) and is the most critical area for water recycling that supplies São Paulo (Zemp et al. 2014). It is also the easiest area to avoid deforestation because all that is required is to not build highways, whereas in most of the rest of Brazilian Amazonia avoiding deforestation requires changing the behavior of millions of people.

Agribusiness interests in the AMACRO region are already planning to expand their operations to the Trans-Purus region (Pontes 2024). Decisions are pending on the highway projects modeled in the present study, and these need to be based on the best possible information on likely impacts. The enormous global and national consequences of these decisions add urgency to the development of reliable models of deforestation in the vast area that would be affected. The present study contributes to this effort.

Up to now, most deforestation has been concentrated in the “arc of deforestation” in the southern and eastern portions of Brazil’s Amazon rainforest, but recent trends show the emergence of new hotspots, pushing the cattle-ranching frontier to the northern part of the Amazon. The impact of existing highways and planned networks linked to BR-319 could promote significant deforestation and forest degradation (Barni et al. 2015; Fearnside 2024; Mataveli et al. 2021).

Roads are an important vector of deforestation in the Brazilian Amazonia because highway construction promotes (i) land grabbing in public lands, increasing deforestation rates and the emergence of new deforestation hotspots; (ii) land conflicts between local communities and migrant deforestation actors; (iii) forest degradation by logging and forest fire, and (iv) emergence of illegal secondary roads (i.e., “*ramais”*) into forest areas, spreading deforestation far from the main roads (Barber et al. 2014; Laurance et al. 2002). This is especially true if roads traverse vulnerable land categories, such as “undesignated public forests” (i.e., government land that has not been designated as a protected area, a settlement or other specific use). These areas are very susceptible to illegal occupation and deforestation, and roads in these areas provide access for land grabbers, loggers and squatters (Azevedo-Ramos et al. 2020; Carrero et al. 2022; Kruid et al. 2021). The term “land grabbers” (*grileiros*) in Amazonia refers to large operators who illegally claim government land and usually obtain or try to obtain legal title, traditionally using various means of corruption but now increasingly through legal channels created by successive “land-grabbers laws;” the claimed land is usually subdivided and sold to cattle ranchers (Carrero et al. 2022; Fearnside 2008).

Amazonas state has the largest area of undesignated public forest in Brazilian Amazonia: 397,588 km^2 or 69% of the total (Alencar et al. 2021). Most of this area is in the Trans-Purus region. Planned roads connecting to BR-319 would open this area to the entry of deforestation actors and processes (Fearnside et al. 2020; Santos et al. 2023).

Undesignated public forest is known as a “no-man’s land” because these areas are untitled. Land grabbers believe that they can freely occupy and clear these areas and then request a land title (Azevedo-Ramos et al. 2020; Brito et al. 2019). Brazil’s Rural Environmental Registry (CAR, *Cadastro Ambiental Rural*) is used, in practice, to justify land-tenure claims, a process known as “illusory legality” (Moutinho et al. 2022). The number of Brazil’s Rural Environmental Registry claims is increasing, as is the size of landholdings in undesignated public forests, showing that this land category is a target for large land grabbers. We use the term “landholdings” rather than “properties” so as not to imply that these areas have legal title.

This study simulates the impact of planned roads on deforestation and illegal land occupation in the last large remaining block of Brazil’s Amazon rainforest. We project these processes up to 2070 considering undesignated public forests, protected areas and settlement projects in a key region in the Brazilian state of Amazonas.

2. Methods

2.1. Study area

The study area encompasses 429,442 km^2 of Brazil's Amazon rainforest and covers 27% (415,306 km^2) of Amazonas state and 6.0% (14,137 km^2) of Rondônia state (Fig. 1). As of 2021, 89% (382,622 km^2) of the total study area remained under forest. Out of this total, 43% (164,998 km^2) was in undesignated public forests, 13% (47,800 km^2) in Indigenous lands, 33% (124,984 km^2) in conservation units (full protection: 9.0% and sustainable use: 24%), 0.4% (1479 km^2) in federal settlement projects (PAs: *projetos de assentamento federal*) and 5.3% (20,176 km^2) in environmentally distinctive settlement projects: agroextractivist settlement projects (PAEs: *projetos de assentamento agroextrativista*) and sustainable development settlement projects (PDSes: *projetos de assentamento de desenvolvimento sustentável*). Additionally, 12% (46,100 km^2) of the forest in 2021 was in landholding areas that could be overlapping with other land categories (e.g., protected areas and undesignated public forests). Of the total number of landholdings in the study area (18,311), 54% (9815) were either landholdings legally titled by the Terra Legal program or areas registered in the Brazil's National Institute for Colonization and Agrarian Reform (INCRA) system for managing agrarian information in rural areas of Brazil (SIGEF, *Sistema de Gestão Fundiária*). The remaining 8496 landholdings (or 46%) were Rural Environmental Registry claims not registered in the SIGEF.

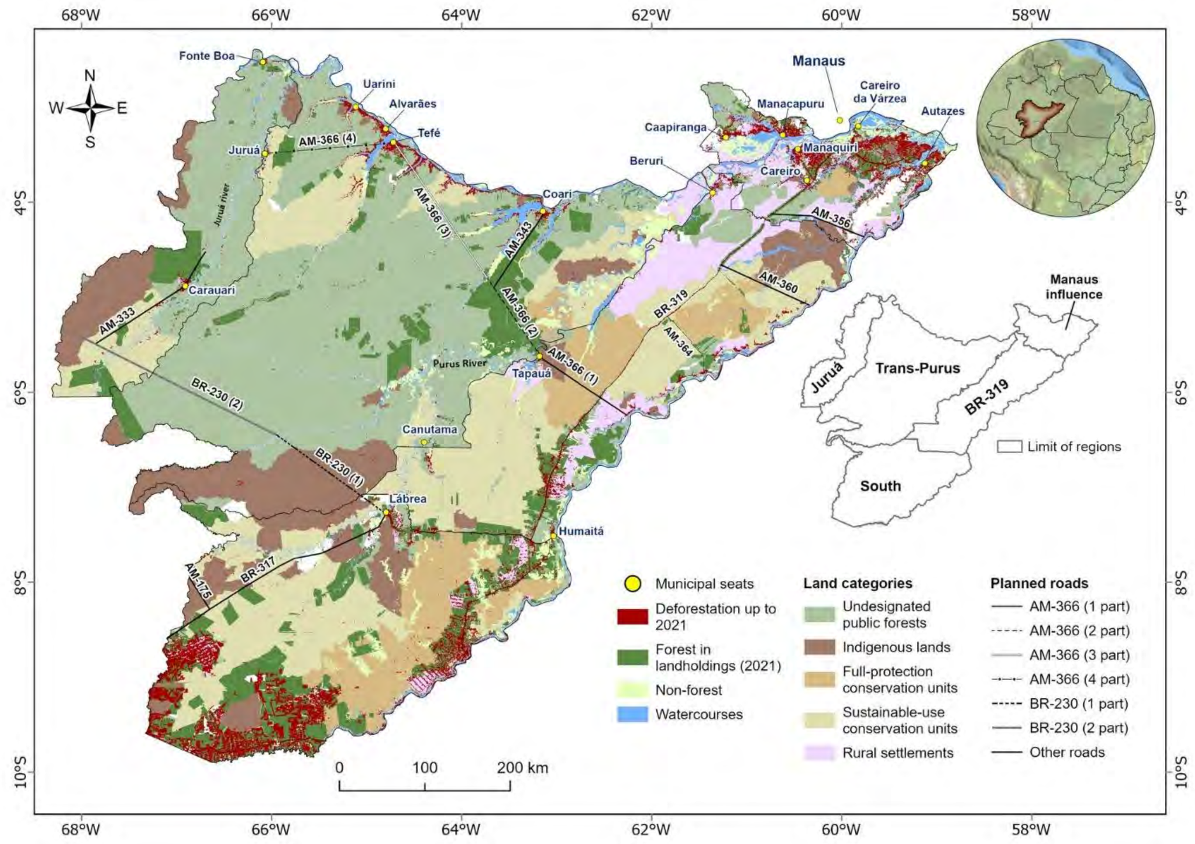

Fig. 1 Distribution of planned highways and landholdings (2021) in five regions of the study area. Areas in white are forest without land-category information.

The study area is divided into five regions: Trans-Purus (170,282 km^2), BR-319 (85,609 km^2), Manaus influence (31,193 km^2), Juruá (44,376 km^2) and South (97,983 km^2)

(Fig. 1). The regions with the highest deforestation up to 2021 were South (10,898 km^2) and Manaus influence (4926 km^2). The Trans-Purus region is the largest (170,282 km^2), covering 39.7% of the study area, but the total deforestation in the Trans-Purus region up to 2021 represents only 1.4% (2362 km^2) of the Trans-Purus region and 0.5% of the total study area. Construction of state and federal highways is planned in the study area. Because there are no official completion dates, we have proposed hypothetical dates for simulation purposes (Fig. 1 and Online Resource 1).

Deforestation dynamics differ among the regions in the study area. In the southern as well as the northeast portion of the area (municipalities near Manaus), deforestation is more intense compared to central portion (Trans-Purus region). In the Trans-Purus region, most deforestation is close to rivers or around urban areas (e.g., Coari and Tefé municipalities). In contrast, in the South region the road network is much denser and has a strong association with deforestation and forest degradation.

2.2. Trans-Purus model

The Trans-Purus model produces spatially explicit simulations designed to project the potential impact of planned highways on deforestation and illegal land occupation, considering the forests in landholdings and in land categories such as undesignated public forests and protected areas (Online Resource 2). In each simulation time step, the model generates an annual map showing predicted deforestation. When highways are constructed during the simulation, there is an increase in landholdings in forest areas (Online Resource 3), representing the attraction of land grabbers from the arc of deforestation to forest near highways. Therefore, new landholdings that emerge during the model simulation are treated as illegal land occupations that have a high risk of being cleared, contributing to the spread of deforestation. The occurrence of deforestation within these landholdings depends on their locations within the land categories, the probability map of deforestation and the deforestation rates associated with the region and the land categories. The establishment of landholdings along a highway begins three years prior to the construction itself (Online Resource 1). This three-year period represents the time when a significant increase in deforestation would occur due to land speculation in the area that is expected to receive the planned infrastructure (Ramos et al. 2018).

The size of the landholdings up to 2021 varied from 10 ha to 250,590 ha. This largest landholding is in the Juruá region, and it was registered as "private property" in INCRA's SIGEF. The data on landholdings up to 2021 were obtained from the Brazilian Agriculture and Ranching Atlas (https://atlasagropecuario.imaflora.org/).

The transition from forest to deforestation was categorized by its location in (i) small landholdings (≤100 ha); (ii) large landholdings (>100 ha); and (iii) "unknown," representing all clearing outside a landholding when its area or size could not be identified. We considered the "unknown" category to encompass the dynamic of deforestation that occurs around urban areas, along rivers and in areas outside of landholdings in undesignated public forests and protected areas when we could not identify the type of actor. This category also represents deforestation in settlement projects because a more detailed analysis is needed to assess land-tenure concentration in these projects (Yanai et al. 2020). The small and large landholding categories considered here refer to spontaneous occupation, which results in chaotic and disordered land distribution (Yanai et al. 2022).

The Trans-Purus model was developed in Dinamica-EGO (Environment for Geoprocessing Objects) software (https://csr.ufmg.br/dinamica/). The Dinamica-EGO environmental modeling platform allows the development of spatial-temporal land-use and land-cover change models that are multi-regional and include iterations with dynamic feedback (Soares-Filho et al. 2009).

The spatially explicit simulation models developed in Dinamica-EGO are based on cellular automata that follow a set of transition rules (e.g., spatial variables that explain the change and model parameters adjusted to control the transition rules). Thus, the transition of a cell (pixel) from one state (e.g., forest) to another (e.g., deforestation) depends on the state of the neighboring cells (Soares-Filho et al. 2002). All cells are updated simultaneously at each time step of the modeling process. Thus, the spread of deforestation depends on region-specific parameters, including the number of forest cells to be cleared in each model time step (i.e., deforestation rates), spatial variables (e.g., proximity to roads and previous deforestation), weights-of-evidence assigned to the spatial variables, and the sizes and shapes of deforestation patches (Soares-Filho et al. 2002).

To project the future impact of highway-construction decisions on deforestation and illegal land occupation, two scenarios were run to show the deforestation trajectory from 2022 to 2070: the business-as-usual scenario and the baseline scenario. In the business-as-usual scenario, it is assumed that (i) the planned federal and state highways are constructed following the construction schedule used in this study, (ii) undesignated public forests surrounding the planned highways and the secondary roads connected to these highways will be highly attractive to land grabbers, encouraging illegal land occupation and deforestation and contributing to a deforestation pattern similar to that observed in regions with high deforestation pressure (i.e., the South and BR-319 regions of the study area), and (iii) the recent trends in deforestation rates will continue, with an anticipated increase as forest areas near roads become occupied, mainly within undesignated public forests. The deforestation pattern observed since 2010 in the municipality of Lábrea, in the South region, illustrates both the rapid pace of deforestation and the transformation of small initial clearings into a consolidated landscape of large clearings (Cabral et al. 2024). The baseline scenario considers the historical trend in deforestation rates in each region of the study area and assumes that there will be no construction of planned highways and no improvement in the existing highways. In this scenario, the Trans-Purus and Juruá regions will continue to have low deforestation rates, and there will be no stimulation of increased illegal occupation due to road construction. This scenario therefore serves as a control for assessing the impact of implementing planned infrastructure.

2.3. Input data

The inputs to the model were maps of land cover of 2009 (calibration step), 2015 (validation), and 2021 (simulation of scenarios), landholdings and regions, and the friction map for calculating the probability of building secondary roads. Maps used to explain the spatial pattern of deforestation and that were considered in deriving the weights-of-evidence coefficients are presented in Online Resource 3. Maps of distance to deforestation and distance to current roads were updated during the model runs in accordance with the simulated increments in deforestation and roads. The spatial resolution used in the maps was 250 m (pixel area: 6.25 ha), which is the minimum area for mapping of Brazil's Deforestation Monitoring Program (PRODES) of the National Institute for Space Research (INPE).

2.4. Model calibration and validation

The calibration consists of adjusting the input variables and internal parameters of the model to improve the similarity between projected outcomes and "real" patterns of change (the "real" pattern is based on PRODES, which has an error of approximately 10%). Two important tasks in calibration are the selection of variables that explain future deforestation and the tuning of parameters that control the transition rules (i.e., from forest to deforestation) (Mas et al. 2018). In our study, we found that the most important drivers of deforestation are proximity to previous deforestation, proximity to roads, and the susceptibility of the land category (such as undesignated public forest). We also ran the model using biophysical variables such as slope, altitude, soil type, and vegetation type, but we found that the spatial pattern of deforestation without these variables produced a more realistic result. Validation is a procedure demonstrating that the model's simulation performance is acceptable for the proposed application and satisfactorily reflects the "real" trends (Oreskes et al. 1994; Rykiel 1996).

In the calibration step, we used the initial (2009) land-cover map to run the model up to 2015. In the validation step, we used the land-cover map for 2015 and ran the model up to 2021. To measure the accuracy of model output, the predicted spatial pattern of deforestation was compared to the observed deforestation from 2015 to 2021 using a fuzzy similarity comparison method with a constant decay function in multiple window sizes (features available in Dinamica-EGO software). The spatial fit of the model was assessed in different window sizes (i.e., number of pixels), with a constant decay function assigning a pixel value equal to 1 to cells in the windows and 0 outside the window (Mas et al. 2018). Similarity between projected and observed deforestation could range from 0% (completely different) to 100% (identical). Additionally, a null model was run, where all weights-of-evidence coefficients were set to zero, resulting in a random allocation of deforestation in the landscape (Hagen-Zanker and Lajoie 2008; Negret et al. 2019).

The allocation of projected deforestation is based on the transition probability map produced at each time step of the simulation. High values in the transition probability map indicate areas of forest most likely to be cleared. The landscape map of the current year, input variable maps (Online Resource 4), and weights-of-evidence coefficients are used to produce the transition probability maps.

The weights-of-evidence method used in Dinamica-EGO is an adaptation of the Bayesian method of conditional probability (Bonham-Carter et al. 1989). Higher values of the weights-of-evidence coefficients indicate that the association between the explanatory variable (e.g., distance to roads) and the probability of forest being cleared is stronger. Negative values indicate an inhibiting effect on deforestation. Values close to zero indicate no association between the deforestation and the explanatory variable for a specific category or distance range (Soares-Filho et al. 2013). The weights-of-evidence coefficient was calculated from 2009 to 2015, with the values being calibrated by making a series of model runs until the spatial pattern of projected deforestation showed a deforestation pattern similar to an observed pattern in the land-cover map.

In the Trans-Purus and Juruá regions, the business-as-usual scenario was run using weights-of-evidence calculated by considering the BR-319 and South region as merged. This was based on the assumption that the projected spatial pattern of deforestation in the Trans-Purus and Juruá regions will be similar to those in the South and BR-319 regions. This change was made only for deforestation that occurred within landholdings. For areas outside the landholdings in the Trans-Purus and Juruá regions, we maintained the same weights-of-evidence coefficients used in the baseline scenario.

All variables used as deforestation predictors in the weights-of-evidence should be conditionally independent. The Cramer test was used to assess spatial correlation between the variables, and values ≥ 0.50 were excluded (Almeida et al. 2003) (Online Resource 5).

The model achieved a minimum similarity of 51% in a 9×9 window size (i.e., within a search radius of 2 km). In contrast, the null model (in the same area as the calibrated model) had a lower minimum similarity value (25%), indicating that the calibrated model had better spatial performance compared to the null model (Online Resource 6).

2.5. Deforestation rates

The “deforestation rates per landholding type” (DR_Land_t) were projected considering the scenario assumptions and historical deforestation rates in each region. In the baseline scenario it was assumed that deforestation rates will follow the historical trend (2010-2021) in all regions. In the business-as-usual scenario, the assumption for the BR-319 and South regions was that deforestation rates will follow a recent (2016-2021) trend with high rates throughout the simulated period. In the case of the Trans-Purus, Juruá and Manaus influence regions, we assumed that before the beginning of illegal land occupation due to the planned highways, the rates were similar to the baseline scenario, and that subsequently the trends in deforestation rates were similar to the BR-319 and South regions (2016-2021) (Online Resource 7), with an anticipated increase as forest areas near planned highways become occupied by landholdings beginning three years prior to the road construction.

An equation adapted from the anthropogenic pressure equation developed by Soares-Filho et al. (2004) was used to estimate the deforestation rates in the BR-319 and South regions, which are hotspot areas that represent the way illegal land occupation and road networks contribute to deforestation. This equation was also applied in the Trans-Purus, Manaus influence, and Juruá regions when land occupation begins due to highway construction. Thus, deforestation is expected to accelerate in the business-as-usual scenario, while in the baseline scenario we expect to see annual deforestation rates maintain the historical mean.

Deforestation rates were estimated annually for each region in the study area. Therefore, both the deforestation trend in each region and the assumptions of the different scenarios will influence the simulated deforestation rates. The calculated values represent the percentages of exposed forest in the different landholding types that will be cleared per year (i.e., net rates of deforestation). During the simulation, after the net rate of deforestation was calculated, the model converts this net rate into a gross rate (i.e., the number of pixels of forest to be cleared) by multiplying the number of pixels of exposed forest present at a given time step by the value estimated in the deforestation rate equation (eq. 1). It is therefore possible to estimate the area (ha) of annual deforestation in the different landholding types based on the number of pixels that changed from forest to deforestation (Soares-Filho et al. 2004, 2009). This forest area tends to decrease over time in the baseline simulation. However, in the business-as-usual simulation, an increase of exposed forest area during a model run is expected due to the incorporation of this forest area as forest within landholdings.

$$\boldsymbol{DR\_Land_t} = \left(\frac{\frac{\left(EF_t \times EFD_{(t0-t1)}\right)+D_t}{(D_t+EF_t)}}{\frac{D_t}{(D_t+EF_t)}} \right) - 1 \times AF \qquad \text{(eq. 1)}$$

DR_Land_t is the “deforestation rate per landholding type” at time t (i.e., at the current time step in the simulation). EF_t is the area of exposed forest at time *t*. The term $EFD_{(t0-t1)}$ refers to a percentage mean of exposed forest converted to deforestation per year in the specified time interval. The period and the value used depend on the model step and scenario assumptions (Online Resources 7 and 8). D_t refers to the area of cumulative deforestation at time *t* for each landholding type. The term AF (acceleration factor) refers to a parameter used to adjust the rate by gradually increasing deforestation over the simulation in response to the increment of new landholdings and highways in the case of the business-as-usual scenario (Online Resource 9). In the baseline scenario, the acceleration factor values were adjusted to maintain the dynamic of deforestation (2010-2021) in the existing landholdings in the BR-319 and South regions. The values used in the acceleration factor were adjusted based on several runs of model simulations.

In the case of deforestation rates for the "unknown" category, for all scenarios the annual deforestation rates were based on the random selection of minimum and maximum values estimated from the transition rates (2010-2021) (Online Resource 10). We used this approach because, for this category, it was assumed that the deforestation patterns in terms of allocation and rates do not change over the course of the simulation.

3. Results

3.1. Projection of deforestation

For the study area as a whole, the business-as-usual scenario cleared 35,095 km^2 more than in the baseline scenario up to 2070. The increment of simulated deforestation (2022-2070) resulted in a reduction by 15% (57,818 km^2) of the total remaining forest present in 2021 (382,622 km^2) for the business-as-usual scenario and of 5.9% (22,723 km^2) for the baseline scenario. In the business-as-usual scenario, due to the presence of planned roads and the increment of simulated landholdings, most deforestation was in three regions: the South, with the largest area cleared (32,972 km^2), followed by the Trans-Purus (20,979 km^2), and the BR-319 (13,532 km^2). The Trans-Purus region had the largest increment of deforestation from 2022 to 2070 (17,470 km^2) between the business-as-usual and baseline scenarios, followed by the BR-319 region (8263 km^2) and South region (6344 km^2). The smallest differences between scenarios occurred in the Manaus influence region (1700 km^2) and the Juruá region (1319 km^2).

In existing landholdings (up to 2021) and in simulated landholdings (2022-2070), we found that the area of forest loss in landholdings with ≤100 ha occurred mainly in the Manaus influence region and in the South region. This pattern was observed in the initial year (2021) and in all simulated scenarios. The total area cleared in these two regions represented 88% (baseline scenario) and 78% (business-as-usual scenario) of the total deforestation in this type of landholding up to 2070 (Table 1). For landholdings >100 ha in area, the largest percentage of forest loss (82%) in the baseline scenario was in the South region. In the case of the business-as-usual scenario, deforestation was primarily in three regions: South (38%), Trans-Purus (34%), and BR-319 (19%) (Table 1).

Table 1 Cumulative deforestation in the initial landscape (PRODES) up to 2021 and in the simulated scenarios in 2070. The PRODES and the baseline scenario consider only landholdings existing up to 2021, while the business-as-usual scenario considered the existing and simulated landholdings up to 2070.

Landholding type	Region	PRODES (2021)		Baseline (2070) Landholdings up to 2021		Business-as-usual (2070) Landholdings up to 2021 + simulated increment (Online Resource 2)	
		Deforestation (km^2)	**%**	**Deforestation (km^2)**	**%**	**Deforestation (km^2)**	**%**
≤100 ha							
	Trans-Purus	76	3.3	139	4.0	529	12.0
	BR-319	132	5.7	247	7.0	383	8.7
	Manaus influence	997	43.0	1,506	42.8	1,601	36.4
	Juruá	32	1.4	41	1.1	62	1.4
	South	1,079	46.6	1,587	45.1	1,827	41.5
	Total	**2,316**	**100**	**3,519**	**100**	**4,402**	**100**
>100 ha							
	Trans-Purus	205	2.8	321	2.0	17,470	33.5
	BR-319	421	5.6	1,378	8.2	10,094	19.3
	Manaus influence	858	11.5	1,253	7.5	3,226	6.2
	Juruá	64	0.9	74	0.4	1,371	2.6
	South	5,900	79.2	13,712	81.9	20,040	38.4
	Total	**7,448**	**100**	**16,738**	**100**	**52,201**	**100**

In the Trans-Purus region, clearing up to 2021 in landholdings with >100 ha accounted for only 1.5% (205 km^2) of the total occupied or claimed area (14,109 km^2). In a business-as-usual scenario simulating new landholdings in the Trans-Purus region, deforestation up to 2070 in landholdings with >100 ha accounted for 47% (17,470 km^2) of the total claimed area (37,566 km^2). For landholdings with ≤100 ha, deforestation accounted for 29% (76 km^2) up to 2021, and the business-as-usual scenario indicated that 77% (529 km^2) of the total area in this landholding category would be cleared by 2070 (Fig. 2).

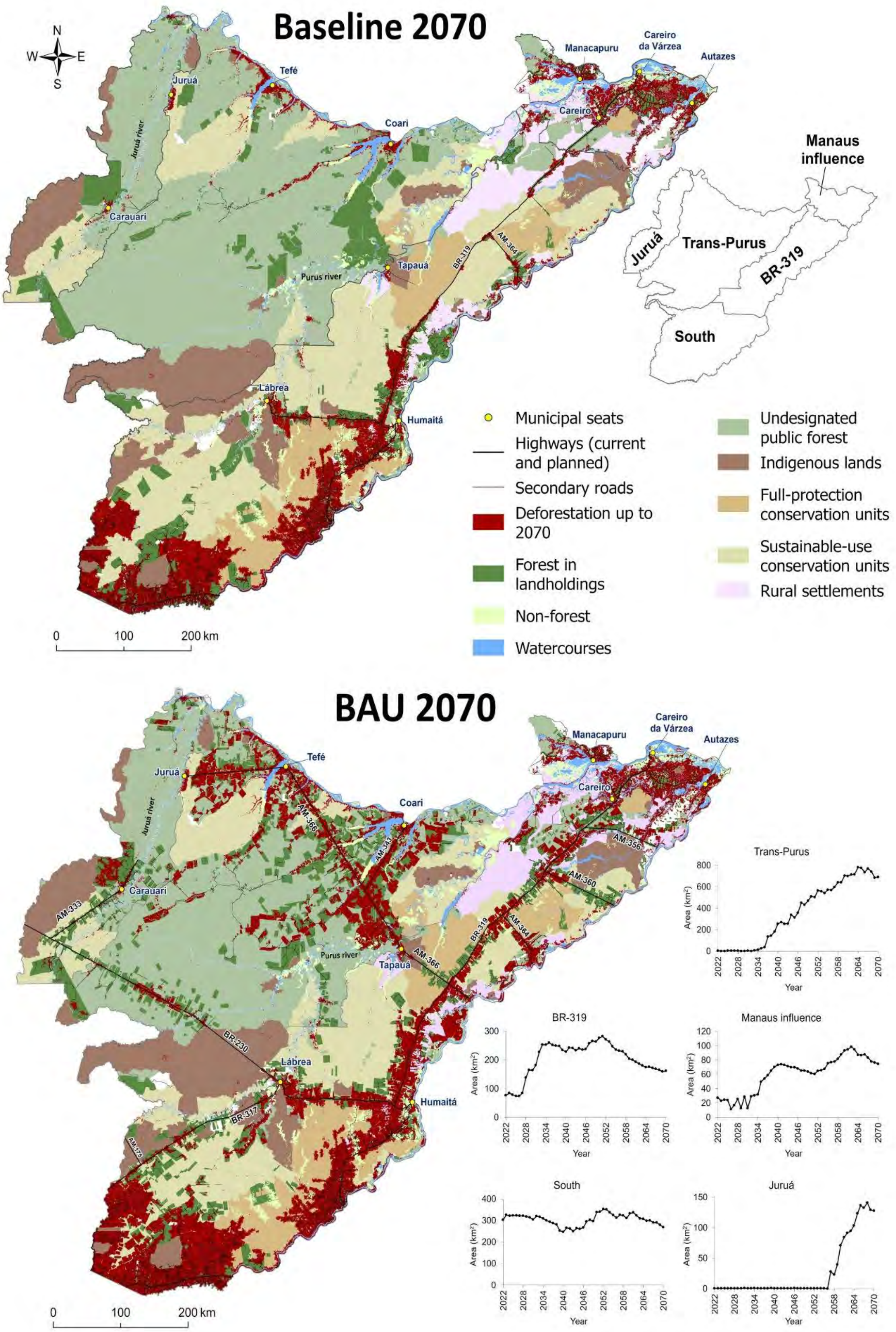

Fig. 2 Baseline and business-as-usual scenarios for the study area in 2070. The graphs on the right in the business-as-usual scenario show deforestation (km^2) per year from 2022 to 2070 in areas occupied by landholdings.

Without the simulation of new landholdings, there is a tendency for the annual cleared area to gradually decrease due to the reduction of available (exposed) forest in the landholdings. Therefore, regions with larger available forest areas in landholdings tended to have larger areas cleared.

Table 2 presents the mean simulated deforestation per year in each region, considering both the overall region areas and distinct landholding categories. In the Trans-Purus, Manaus influence and Juruá regions, the period following the building of planned highways had higher yearly cleared areas compared to the pre-road period. This trend occurred both in each region as a whole and in each landholding category. In the Trans-Purus region, the mean deforestation prior to the implementation of planned highways was 23 km^2 per year for this region as a whole and 2 km^2 for landholdings with >100 ha. In the scenario with the planned highways, the mean deforestation per year increased to 483 km^2 in this region as a whole and 454 km^2 in landholdings with >100 ha (Fig. 3 and Table 2).

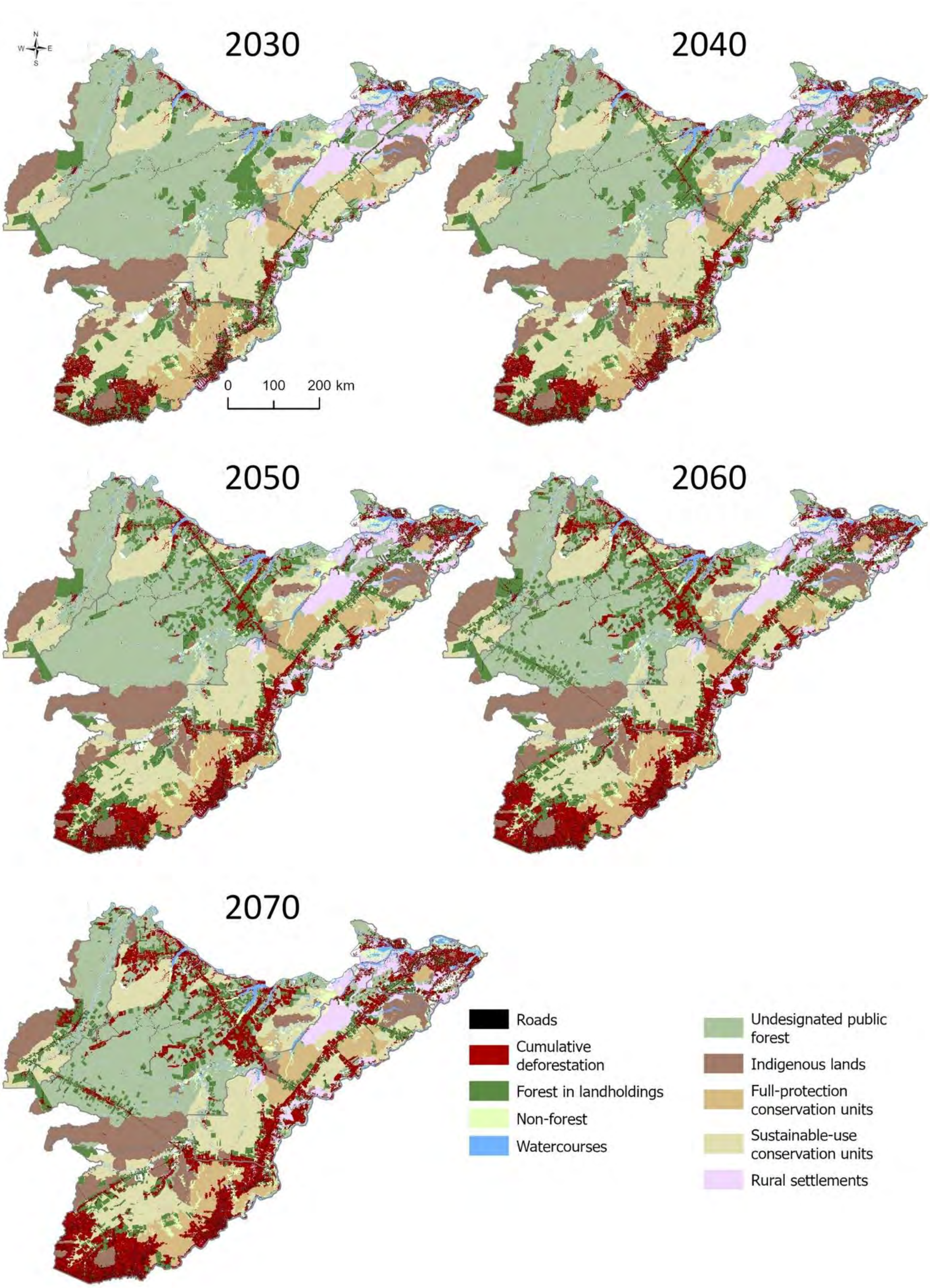

Fig. 3 Trajectory of deforestation in the business-as-usual scenario for the study area from 2030 to 2070.

Table 2 Mean deforestation per year (km^2) considering the period before and after planned highways. "After planned highways" refers to the year that the increment of landholdings started (i.e., 3 years before each highway is built in the simulation).

Region	Category	Mean deforestation per year (km^2)	
		Before planned highways	After planned highways
Trans-Purus		Period: 2022-2032	Period: 2033-2070
	Region as a whole	23	483
	Landholdings ≤100 ha	2	12
	Landholdings >100 ha	2	454
Manaus influence		Period: 2022-2031	Period: 2032-2070
	Region as a whole	47	95
	Landholdings ≤100 ha	12	12
	Landholdings >100 ha	9	58
Juruá		Period: 2022-2056	Period: 2057-2070
	Region as a whole	3	97
	Landholdings ≤100 ha	0	2
	Landholdings >100 ha	0	93

		Mean deforestation per year (km^2) for the entire simulation period (2022-2070)
BR-319		
	Region as a whole	235
	Landholdings ≤100 ha	5
	Landholdings >100 ha	197
South		
	Region as a whole	451
	Landholdings ≤100 ha	15
	Landholdings >100 ha	289

3.2. Projection of deforestation in land categories

Land categories in the study area include undesignated public forest, settlement projects, and protected areas. Undesignated public forest showed the most substantial cumulative deforestation, reaching 4725 km^2 by 2021 and projections of 16,889 km^2 (baseline scenario) and 39,139 km^2 (business-as-usual scenario) by 2070 (Table 3). Considering the total area of undesignated public forest, deforestation in the business-as-usual scenario up to 2070 showed an increase of 728% (34,414 km^2) compared with PRODES (2021) and a 132% increase (22,250 km^2) compared with the baseline (2070). Due to its extensive area of undesignated public forests, the Trans-Purus region showed the largest cleared area (16,711 km^2) in the business-as-usual scenario up to 2070. The South and BR-319 regions also had significant deforestation in undesignated public forest in the business-as-usual scenario, with total areas of 11,456 km^2 and 6551 km^2, respectively. In the business-as-usual scenario, the reduction of remaining forest area (inside and outside of landholdings) from 2022 to 2070 in undesignated public forest occurred mainly in the Trans-Purus region (16,328 km^2 or 15% in relation to 2021 within this region), the South region (8586 km^2 or 78%) and the BR-319 region (5852 km^2 or 53%) (Table 3 and Online Resource 11).

[Table 3 here]

The total area cleared in federal settlement projects (*projetos de assentamento federal*) was similar in the baseline (2275 km^2) and business-as-usual (2227 km^2) scenarios up to 2070, showing increases of 83% (baseline) and 79% (business-as-usual) compared to 2021. Most federal settlement projects in the study area are in the Manaus influence region and the South region, making these regions account for the greatest portions of deforestation in this land category. In the case of "environmentally distinctive" settlement projects, namely agroextractivist settlement projects (*projetos de assentamento agroextrativista*) and sustainable development projects (*projetos de assentamento de desenvolvimento sustentável*), the initial year (2021) and both scenarios showed that the BR-319 region and the Manaus influence region accounted for most of the deforestation. These two regions had 3129 km^2, or 83% of the 3764 km^2 total deforestation in environmentally distinctive settlement projects in the business-as-usual scenario, representing an increase of 63% (1206 km^2) in comparison to the baseline scenario (Table 3).

Indigenous lands showed less deforestation in terms of area compared with conservation units (protected areas for biodiversity) (Table 3 and Online Resources 12 – 14). Overall, the scenarios projected deforestation in Indigenous lands totaling 843 km^2 in the baseline scenario and 884 km^2 in the business-as-usual scenario, a difference of 4.9% (41 km^2) between the business-as-usual scenario and the baseline scenario for the study area as a whole. The BR-319 region showed the largest increment in cleared area (76 km^2) in Indigenous lands in the business-as-usual scenario, representing a 125% increase compared with the baseline scenario. For full-protection conservation units, both scenarios showed similar projections in terms of total deforestation up to 2070, with a difference of 216 km^2 between them. However, there was a large increase of 2692 km^2 (1249%) in deforestation in the baseline scenario and of 2476 km^2 (1149%) in the business-as-usual scenario compared with PRODES (2021). The South region accounted for most of the deforestation in full-protection conservation units. In the baseline scenario, the South region had 226 km^2 (8.7%) more deforestation than in the business-as-usual scenario. In both scenarios, most of the deforestation in full-protection conservation units was allocated outside of landholdings. For sustainable-use conservation units, the business-as-usual scenario had the largest deforestation (8706 km^2) up to 2070.

Comparing the scenarios, the business-as-usual scenario had 6729 km^2 (341%) more deforestation than the baseline scenario. In addition, there were increases of 958 km^2 (99%) in deforestation in the baseline scenario and 7715 km^2 (778%) in the business-as-usual scenario compared with PRODES (2021). Two regions concentrated 85% of the total deforestation in sustainable-use conservation units in the business-as-usual scenario, the South region with 47% (4112 km^2) and the BR-319 region with 37% (3246 km^2). In these two regions, the landholdings with >100 ha accounted for the largest portion (>85%) of the projected deforestation in relation to the total deforestation simulated in the business-as-usual scenario.

4. Discussion

4.1. Deforestation scenarios and modeling approach

Construction of planned highways in key regions of Amazonas state would promote illegal land occupation (including land grabbing) and deforestation, especially in the Trans-Purus region. The remaining forest in this region would be threatened by the emergence of a new deforestation hotspot area when roads bring loggers and cattle ranchers from the arc of deforestation. In the business-as-usual scenario, the Trans-Purus, BR-319, and South regions showed increases of deforestation up to 2070. The South and BR-319 regions are currently the scene of illegal deforestation for cattle ranching, of forest degradation by logging and fire and of land conflicts between land grabbers and traditional communities (e.g., extractivists and Indigenous peoples) (Andrade et al. 2021; Mataveli et al. 2021). The same causes of deforestation are expected to spread to the Trans-Purus and Juruá regions with the expansion of the deforestation frontier to these areas. Although we did not specify a particular year for the paving of the BR-319 highway in the business-as-usual scenario, it is expected that the land occupation around the BR-319 highway will increase in the simulation from 2028 to 2035 when the first part of AM-366 highway is assumed to be constructed, connecting the Boca do Acará community (on the Madeira River) to the municipal seat of Tapauá (on the Purus River).

In the Trans-Purus region, the mean annual deforestation from the beginning of land occupation (2033) to the end of the simulation (2070) was 483 km^2 $year^{-1}$. This value represents 30.7% of the mean annual deforestation (1574 km^2) estimated by PRODES for Amazonas state from 2016 to 2022, a period marked by the highest deforestation since 2004 (INPE 2024).

Roads are an important driver of deforestation in the Brazilian Amazonia causing a significant impact on the forest in their vicinity (Barber et al. 2014). In the case of BR-319, protected areas were established in its vicinity as a measure to curb deforestation (Pacheco 2024). However, since the area lacks effective monitoring and control to inhibit the access of loggers and land grabbers to these protected areas, the strategy has been shown to have a limited effect in preventing forest degradation, illegal land occupation and conflicts with "extractivists" (communities that harvest Brazil nuts and other non-timber forest products) in conservation units (Ferrante et al. 2021b).

Two modeling studies have projected substantial deforestation in the area along BR-319, but without including the Trans-Purus region or the planned highways that would link it to BR-319 (Fearnside et al. 2009; Soares-Filho et al. 2020). One study that included the Trans-Purus region (Soares-Filho et al. 2006) only considered BR-319, not the construction of the planned roads branching off this highway (e.g., AM-366 and AM-343), resulting in projected deforestation only occurring near areas previously cleared along the BR-319 and Transamazon highways and close to rivers.

Planned highways have been included in two modeling studies that considered the Trans-Purus region (dos Santos Junior et al. 2018; Santos et al. 2023). Our study assumed different years for the construction of these highways. We used an area similar to that used by Santos et al. (2023) for the Trans-Purus region, but our study differed in terms of how deforestation rates were calculated and how the spatial distribution of simulated deforestation was allocated. Our study includes a major advance by incorporating landholdings into the simulation, allowing us to distinguish the dynamics of projected deforestation within different landholding types and in areas outside of the landholdings. This approach, coupled with the increment of new landholdings over time, enhances the spatial representation of deforestation actors' behavior, contributing to a more comprehensive understanding of the deforestation process associated with highway construction and illegal land occupation in the Brazilian Amazonia.

This was particularly important for the Trans-Purus and Juruá regions, as the deforestation dynamics in these areas, both in terms of rates and spatial distribution, differ from those in the BR-319 and South regions. In our study we could represent a deforestation pattern within the landholdings like that in the BR-319 and South regions, while maintaining historical deforestation trends outside the landholdings. These trends were characterized by deforestation along rivers and around the urban areas, with low deforestation rates in the Trans-Purus and Juruá regions. A comparison between the simulation results from our study and those of previous studies (dos Santos Junior et al. 2018; Santos et al. 2023) is presented in Online Resource 15. We note that all these simulations, including the present one, lack a means of representing both large, organized land invasions (as opposed to the gradual entry of individual actors) and the construction of as-yet unplanned major highways (as opposed to small "endogenous" roads). The planned 740,000-km^2 Solimões Sedimentary Area oil and gas project encompasses the entire Trans-Purus region (Consórcio PIATAM/COPPETEC and EPE 2020; Esterhuyse et al. 2022; Fearnside 2020b), making additional highways likely, along with the deforestation these roads would facilitate. These limitations make the resulting scenarios conservative.

4.2. Vulnerability of land categories to deforestation

4.2.1. Undesignated Public Land

Here we focus on undesignated public land and protected areas due to their vulnerability to deforestation, illegal land occupation, and their crucial role in the conservation and protection of forest resources. Together these land categories comprised 83% of the study area and 66% of total deforestation in the business-as-usual scenario. The vulnerability of undesignated public forests is related to the absence of monitoring and control of illegal occupation and deforestation and to the expectation of land grabbers that they will be able to legalize their illegal land occupation in the future (Alencar et al. 2021; Azevedo-Ramos et al. 2020; Yanai et al. 2022). In the business-as-usual scenario, we showed that undesignated public forest will face a dangerous situation with the expansion of the road network connecting the cattle ranching frontier in the arc of deforestation to the central portion of Amazonas state (i.e., the Trans-Purus region). Protected areas near roads will also be susceptible to deforestation and land occupation.

Within the undesignated public forest category, the Trans-Purus region had the largest cleared area up to 2070 (16,711 km^2) compared to other regions of the study area in the business-as-usual scenario. The cleared area in the Trans-Purus region represented 43% of total deforestation in undesignated public forest in the study area. This substantial increase in deforestation is alarming when compared with the baseline scenario up to 2070 (1327 km^2) and the initial year of simulation in 2021 (382 km^2). It reflects the potential future impact resulting from the construction of planned highways and their role in facilitating access for deforestation actors (Fearnside 2022). The simulation of an increased number of landholdings reflects the way that illegal land invasions in the vicinity of highways contribute to deforestation.

We emphasize that the construction of planned highways in key parts of Brazil's Amazon rainforest will promote illegal land occupation and deforestation, especially in the undesignated public lands. The Trans-Purus, a region that encompasses the largest area of undesignated public forests in the Brazilian Amazonia, faces an increased risk of deforestation with the construction of planned state and federal roads. The same spatial deforestation pattern observed in the arc of deforestation could be expected to occur in the Trans-Purus region with the presence of planned highways.

4.2.2. Protected Areas

Our findings indicated that, up to 2070, the area cleared in Indigenous lands was lower than in conservation units in both scenarios (Table 3 and Online Resources 12 - 14). Indigenous lands in areas with high deforestation pressure in the Brazilian Amazonia have been effective at avoiding deforestation (Nolte et al. 2013). Full-protection conservation units had large increases in deforestation up to 2070 in both scenarios, especially in Mapinguari National Park in the South region (Online Resource 16). Qin et al. (2023) showed that full-protection conservation units had only minor forest loss from 2000 to 2013 in the Brazilian Amazonia. However, in the subsequent period (2013-2021), they observed a significant reduction in forest cover in this protected area category. In our study, areas outside of landholdings overlapping full-protection conservation units in the South region reflected the 2013-2021 dynamics reported by Qin et al. (2023). In our case, the spatial pattern of land-cover change was obtained from 2009 to 2015, and the weights-of-evidence coefficient for the full-protection category for areas outside of landholdings (i.e., the "unknown" category) was positive, indicating a higher chance of deforestation compared to Indigenous lands and sustainable-use conservation units, which have negative weights-of-evidence coefficients.

A substantial increase in deforestation occurred in landholdings larger than 100 ha in sustainable-use conservation units in the South and BR-319 regions in the business-as-usual scenario, as compared with the baseline scenario. The increase in illegal land occupation near BR-319 and planned highways would lead to significant forest loss in these conservation units, which tend to be more susceptible than Indigenous lands and full-protection conservation units. See the Online Resource 17 for more details on the dynamics of simulated deforestation in protected areas.

Protected areas are essential tools for biodiversity conservation, climate mitigation, and securing the territories of Indigenous peoples and traditional communities (Nogueira et al. 2018). They have been implemented as strategies to reduce the impact of deforestation in the vicinity of BR-319 (Fearnside et al. 2009). Our deforestation projection up to 2070 indicates that regions already facing high deforestation pressure, such as the South and BR-319 regions in our study area, may experience intensified deforestation spreading into the forest in protected areas. This means that the effectiveness of protected areas in curbing deforestation is likely to be compromised by the presence of roads and land grabbers.

4.2.3. Landholdings

In our study area, 10% (2937 km^2) of the total forest area in landholdings in undesignated public forests was cleared up to 2021 (Online Resource 11). Most of this deforestation (71% or 2094 km^2) took place in landholdings in the South region. The Trans-Purus and Juruá regions had the lowest percentages of cleared area within the landholdings, with 2.1% (62 km^2) and 0.7% (21 km^2), respectively. In the Trans-Purus region, 40% of the landholdings claimed by 2021 were larger than 100 ha. While there is no significant deforestation within these landholdings currently, their strategic proximity or overlap with the planned highways (AM-366 and AM-343) suggests an intentional selection based on the road connection to the BR-319 highway. Proximity to road networks plays a pivotal role in illegal land occupation processes (Moutinho et al. 2022), as forest areas close to roads are more accessible for clearing due to facilitated transport of machinery and workers, as well as for bringing cattle to the cleared areas. The price of land located near roads is much higher than in areas with more difficult access, resulting in speculative profits to land grabbers who claim and subsequently sell land along planned roads. In the business-as-usual scenario, these landholdings were the first to be cleared after the highway's construction. Up to 2070, 59% (32,872 km^2) of the total forest area within the landholdings located in undesignated public forest was cleared in the business-as-usual scenario. Note that our study does not assume that landholders obey Brazil's Forest Code, which would limit clearing to 20% of each landholding; the fact that the 20% limit is ignored is clear from satellite imagery, including imagery for the vicinity of Vila Realidade on BR-319 in the South region of our study area. Of the study area's total deforestation in landholdings in undesignated public forest in the business-as-usual scenario, the Trans-Purus region contributed 48% (15,684 km^2), the South region 25% (8360 km^2), and the BR-319 region 17% (5500 km^2) (for area cleared in each landholding type, see Online Resource 11).

If the planned highways are constructed, it is expected that large deforestation actors will play a major role in occupying and clearing the forest along highways in undesignated public forests. Alencar et al. (2021) found that the sizes of the areas claimed in the Rural Environmental Registry increased between 2016 and 2020, when 44% of total area of Rural Environmental Registry claims in undesignated public forests was in claims larger than 1500 ha, indicating that large actors (probably land grabbers) are the primary parties interested in either occupying these forest areas or selling them who will clear and occupy the land. Large agribusiness and ranching entrepreneurs in the AMACRO deforestation hotspot have plans to move next to the Purus, Juruá and Javari valleys that would be opened by AM-366 in the Trans-Purus and Juruá regions (Pontes 2024).

The future impact of deforestation could be better controlled and curbed if we know who the main actors responsible for deforestation are. Deforestation of the Trans-Purus region would have devastating consequences for the environmental services this area provides, such as recycling the water that supplies rainfall to parts of Brazil outside of Amazonia, including the city of São Paulo (Fearnside 2022). It also plays a crucial role in regulating rainfall for agriculture and storing carbon that avoids a massive emission of greenhouse gases (Leite-Filho et al. 2021; Nogueira et al. 2018). The Trans-Purus region not only provides crucial ecosystem services to Brazil and to the rest of the world, it is also vital for traditional communities and to Indigenous peoples that depend on forest resources for their livelihoods.

5. Conclusion

The construction of planned highways in key regions of Brazil's Amazon rainforest will promote land grabbing and deforestation, especially in undesignated public lands. Thus, it is urgent to protect the remaining forests in this land category from invasion and illegal land occupation. The business-as-usual scenario showed that regions such as Trans-Purus and Juruá that now have a large portion of remaining forest will be very attractive to deforestation with the construction of planned highways. This will result in the expansion of deforestation frontier, turning the Trans-Purus region into a new deforestation epicenter in the Brazilian Amazon. Deforestation dynamics like those in the arc of deforestation (BR-319 and South regions) will be spread in the Trans-Purus and Juruá regions. While our simulations indicate substantial deforestation by 2070, emphasize that the scale and speed of deforestation could be much faster due to processes not included in the model, such as organized land invasions and highway plans not yet announced, including those that may arise from the Solimões Sedimentary Area oil and gas project. We suggest that this scenario must be avoided by restraining the implementation of highways such as BR-319, AM-366 and AM-343.

The incorporation of individual landholdings in our simulation improves projections of the dynamics of deforestation over time, enhancing the spatial representation of deforestation processes linked to road construction and illegal land occupation in the Brazilian Amazon. The results show the need both to forego planned road construction and for major policy changes to halt illegal occupation of government land.

Acknowledgments

Funding: The authors thank the National Institute for Amazonian Research (INPA) (PRJ 15.125), the Amazonas State Research Support Foundation (FAPEAM) (01.02.016301.01073/2023-57); the National Council for Scientific and Technological Development (CNPq) (312450/2021-4, 406941/2022-0 and 150551/2023-1) and the Brazilian Network for Research on Global Climate Change (FINEP/Rede Clima, 01.13.0353-00) for financial support.

The authors thank Britaldo Soares-Filho, Cláudia Almeida, Jerfferson dos Santos and Beatriz Cabral for comments on the manuscript.

Author contributions:
Aurora Miho Yanai: Conceptualization, data curation, formal analysis, investigation, methodology, software, validation, visualization, writing-original draft, writing-review and editing. **Marcos Antonio Isaac Júnior:** Conceptualization, data curation, formal analysis, methodology, software. **Jonathas Nunes da Silva:** Conceptualization, data curation and formal analysis. **Marcelo Augusto dos Santos Junior:** Conceptualization, methodology, writing – review and editing. **Paulo Maurício Lima de Alencastro Graça:** Conceptualization, funding acquisition, resources, supervision, validation, writing – review and editing. **Philip Martin Fearnside:** Conceptualization, funding acquisition, resources, supervision, validation, writing – review and editing.

Competing interests: The authors declare no competing interests.

Data and materials availability: All data available in the main text or online resources will be available on request.

References

Alencar A, Castro I, Laureto L, Guyot C, Stabile M et al (2021) *Amazon on Fire – deforestation and fire in undesignated public forests* (Tech. Rep. nº 7, Amazon Environmental Research Institute). https://ipam.org.br/bibliotecas/amazon-on-fire-deforestation-and-fire-in-undesignated-public-forests/

Almeida CM, Batty M, Monteiro AMV, Câmara G, Soares-Filho BS et al (2003) Stochastic cellular automata modeling of urban land use dynamics: Empirical development and estimation. *Computers, Environment and Urban Systems, 27*(5), 447–453. https://doi.org/10.1016/S0198-9715(02)00042-X

Andrade MBT, Ferrante L, Fearnside PM (2021) Brazil’s Highway BR-319 demonstrates a crucial lack of environmental governance in Amazonia. *Environmental Conservation, 48,* 161–164. https://doi.org/10.1017/S0376892921000084

Arraut JM, Nobre CA, Barbosa HM, Obregon G, Marengo JA (2012) Aerial rivers and lakes: Looking at large-scale moisture transport and its relation to Amazonia and to subtropical rainfall in South America. *Journal of Climate*, 25, 543-556. https://doi.org/10.1175/2011JCLI4189.1

Azevedo-Ramos C, Moutinho P, da S Arruda VL, Stabile MCC, Alencar A et al (2020) Lawless land in no man’s land: The undesignated public forests in the Brazilian Amazon. *Land Use Policy, 99,* 104863. https://doi.org/10.1016/j.landusepol.2020.104863

Barber CP, Cochrane MA, Souza CM, Laurance WF (2014) Roads, deforestation, and the mitigating effect of protected areas in the Amazon. *Biological Conservation, 177,* 203–209. https://doi.org/10.1016/j.biocon.2014.07.004

Barni PE, Fearnside PM, Graça PMLA (2015) Simulating deforestation and carbon loss in Amazonia: impacts in Brazil's Roraima state from reconstructing Highway BR-319 (Manaus-Porto Velho). *Environmental Management, 55*, 259-278. https://doi.org/10.1007/s00267-014-0408-6

Bonham-Carter GF, Agterberg FP, Wright DF (1989) Weights of evidence modeling: A new approach to mapping mineral potential. In *Statistical Applications in Earth Sciences* (Geological Survey of Canada, Paper 89–9). https://publications.gc.ca/collections/collection_2017/rncan-nrcan/M44-89-9-eng.pdf. Accessed 26 November 2024

Bottino MJ, Nobre P, Giarolla E, da Silva Junior, MB, Capistrano VB et al (2024) Amazon savannization and climate change are projected to increase dry season length and temperature extremes over Brazil. *Scientific Reports*, *14*, 5131. https://doi.org/10.1038/s41598-024-55176-5

Brito B, Barreto P, Brandão A, Baima S, Gomes PH (2019) Stimulus for land grabbing and deforestation in the Brazilian Amazon. *Environmental Research Letters, 14,* 064018. https://doi.org/10.1088/1748-9326/ab1e24

Cabral BF, Yanai AM, Graça PMLA, Escada MIS, de Almeida CM et al (2024) Amazon deforestation: A dangerous future indicated by patterns and trajectories in a hotspot of forest destruction in Brazil. *Journal of Environmental Management, 354*, 20354. https://doi.org/10.1016/j.jenvman.2024.120354

Carrero GC, Walker RT, Simmons CS, Fearnside PM (2022) Land grabbing in the Brazilian Amazon: Stealing public land with government approval. *Land Use Policy, 120,* 106133. https://doi.org/10.1016/j.landusepol.2022.106133

Chaves MED, Mataveli G, Conceição KV, Adami M, Petrone FG, Sanches ID (2024) AMACRO: the newer Amazonia deforestation hotspot and a potential setback for Brazilian agriculture. *Perspectives in Ecology and Conservation, 22,* 93-100. https://doi.org/10.1016/j.pecon.2024.01.009

Consórcio PIATAM/COPPETEC (Instituto de Inteligência Socioambiental Estratégica da Amazônia / Fundação Coordenação de Projetos, Pesquisas e Estudos Tecnológicos), EPE (Empresa de Pesquisa Energética) (2020) Estudo Ambiental de Área Sedimentar na Bacia Sedimentar Terrestre do Solimões EAAS Solimões Relatório – SOL-EA-60-600.0010-RE-R0. Consórcio PIATAM/COPPETEC, Manaus, AM and Empresa de Pesquisa Energética (EPE), Rio de Janeiro, RJ, Brazil. 552 pp. https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/estudo-ambiental-de-area-sedimentar-do-solimoes. Accessed 23 August 2025

dos Santos Junior MA, Yanai AM, Sousa Junior FO, de Freitas IS, Pinheiro HP et al (2018) *BR-319 como propulsora de desmatamento: Simulando o impacto da rodovia Manaus-Porto Velho*. Instituto do Desenvolvimento Sustentável da Amazônia – IDESAM. https://idesam.org/simula-desmatamento-br319. Accessed 26 November 2024

Esterhuyse S, Redelinghuys N, Charvet P, Fearnside P, Daga V et al (2022) Effects of hydrocarbon extraction on freshwaters. *Encyclopedia of Inland Waters*, 2nd Edition. Elsevier, Amsterdam, the Netherlands. Vol. 4, pp. 189-209. https://doi.org/10.1016/B978-0-12-819166-8.00164-X

Fearnside PM (2004) A água de São Paulo e a floresta amazônica. *Ciência Hoje, 34*(203), 63-65. https://bit.ly/36GMHAT. Accessed 26 November 2024

Fearnside PM (2008) The roles and movements of actors in the deforestation of Brazilian Amazonia. *Ecology and Society, 13*(1), 23. http://www.jstor.org/stable/26267941

Fearnside PM (2015) Rios voadores e a água de São Paulo. *Amazônia Real,* https://bit.ly/3qykIsY. Accessed 26 November 2024

Fearnside PM (2020a) TransPurus: Amazonia's biogeochemical cycles depend on the fate of the region's largest block of intact forest. American Geophysical Union (AGU) Fall Meeting 2020. Paper GC009-0015. https://doi.org/10.1002/essoar.10506078.1

Fearnside PM (2020b) Oil and gas project threatens Brazil's last great block of Amazon forest (commentary). *Mongabay,* https://news.mongabay.com/2020/03/oil-and-gas-project-threatens-brazils-last-great-block-of-amazon-forest-commentary/. Accessed 23 August 2025

Fearnside PM (2022) Amazon environmental services: Why Brazil's Highway BR-319 is so damaging. *Ambio, 51*(6), 1367–1370. https://doi.org/10.1007/s13280-022-01718-y

Fearnside PM (2024) Impactos da rodovia BR-319. *Amazônia Real*. https://bit.ly/3zTyzTG. Accessed 26 November 2024

Fearnside PM, Graça PMLA (2006) BR-319: Brazil's Manaus-Porto Velho Highway and the potential impact of linking the arc of deforestation to central Amazonia. *Environmental Management, 38*(5), 705-716. https://doi.org/10.1007/s00267-005-0295-y

Fearnside PM, Silva RA (2023) Amazon region hit by trio of droughts in grim snapshot of the century to come. *The Conversation*, 22 November 2023. https://theconversation.com/amazon-region-hit-by-trio-of-droughts-in-grim-snapshot-of-the-century-to-come-217652

Fearnside PM, Graça PMLA, Keizer EWH, Maldonado FD, Barbosa RI et al (2009) Modelagem de desmatamento e emissões de gases de efeito estufa na região sob influência da rodovia Manaus-Porto Velho (BR-319). *Revista Brasileira de Meteorologia, 24*, 208–233. https://doi.org/10.1590/S0102-77862009000200009

Fearnside PM, Ferrante L, Yanai AM, Isaac Júnior MA (2020) Trans-Purus: Brazil's last intact Amazon Forest at immediate risk (commentary). *Mongabay*. https://news.mongabay.com/2020/11/trans-purus-brazils-last-intact-amazon-forest-at-immediate-risk-commentary/. Accessed 26 November 2024

Ferrante L, de Andrade MBT, Leite L, Silva Junior, CA, Lima M et al (2021a) Brazil's Highway BR-319: The road to the collapse of the Amazon and the violation of indigenous rights. *Die Erde, 152*(1), 65-70. https://doi.org/10.12854/erde-2021-552

Ferrante L, Andrade MBT, Fearnside PM (2021b) Land grabbing on Brazil's Highway BR-319 as a spearhead for Amazonian deforestation. *Land Use Policy, 108,* 105559. https://doi.org/10.1016/j.landusepol.2021.105559

Flores BM, Montoya E, Sakschewski B, Nascimento N, Staal A et al (2024) Critical transitions in the Amazon forest system. *Nature, 626*, 555–564. https://doi.org/10.1038/s41586-023-06970-0

Hagen-Zanker A, Lajoie G (2008) Neutral models of landscape change as benchmarks in the assessment of model performance. *Landscape and Urban Planning, 86*(3–4), 284–296. https://doi.org/10.1016/j.landurbplan.2008.04.002

INPE (Instituto Nacional de Pesquisas Espaciais). (2024) *Desmatamento – Amazônia Legal, version 1, Programa de Monitoramento da Amazônia e demais Biomas*. http://terrabrasilis.dpi.inpe.br/downloads/

Kruid S, Macedo MN, Gorelik SR, Walker W, Moutinho P et al (2021) Beyond deforestation: Carbon emissions from land grabbing and forest degradation in the Brazilian Amazon. *Frontiers in Forests and Global Change*, *4*, 645282. https://doi.org/10.3389/ffgc.2021.645282

Lapola DM, Pinho P, Barlow J, Aragão LEOC, Berenguer E et al (2023) The drivers and impacts of Amazon forest degradation. *Science, 379*, eabp8622. https://doi.org/10.1126/science.abp8622

Laurance WF, Albernaz AKM, Schroth G, Fearnside PM, Bergen S et al (2002) Predictors of deforestation in the Brazilian Amazon. *Journal of Biogeography, 29*, 737–748. https://doi.org/10.1046/j.1365-2699.2002.00721.x

Leite-Filho AT, Soares-Filho BS, Davis JL, Abrahão GM, Börner J (2021) Deforestation reduces rainfall and agricultural revenues in the Brazilian Amazon. *Nature Communications, 12*(1), 2591. https://doi.org/10.1038/s41467-021-22840-7

Lovejoy TE, Nobre C (2018) Amazon tipping point. *Science Advances,* 4, art. eaat2340. https://doi.org/10.1126/sciadv.aat2340

Marengo JA, Souza CM, Thonicke K, Burton C, Halladay K et al (2018) Changes in climate and land use over the Amazon region: Current and future variability and trends. *Frontiers in Earth Science, 6*, 228. https://doi.org/10.3389/feart.2018.00228

Martinez JA, Dominguez F (2014) Sources of atmospheric moisture for the La Plata River Basin. *Journal of Climate,* 27, 6737–6753. https://doi.org/10.1175/JCLI-D-14-00022.1

Mas JF, Paegelow M, Olmedo MTC (2018) LUCC Modeling approaches to calibration. In *Geomatic Approaches for Modeling Land Change Scenarios* (pp. 11–25). Lecture Notes in Geoinformation and Cartography. Springer Nature. https://doi.org/10.1007/978-3-319-60801-3_2

Mataveli GAV, Chaves MED, Brunsell NA, Aragão LEOC (2021) The emergence of a new deforestation hotspot in Amazonia. *Perspectives in Ecology and Conservation, 19*, 33–36. https://doi.org/10.1016/j.pecon.2021.01.002

Matricardi EAT, Skole DL, Costa OB, Pedlowski MA, Samek JH et al (2020) Long-term forest degradation surpasses deforestation in the Brazilian Amazon. *Science, 369*, 1378–1382. https://doi.org/10.1126/science.abb3021

Moutinho P, Alencar A, Stabile M, Fellows M, Salomão CSC et al (2022) *Destinação de Florestas Públicas: Um meio de combate à grilagem e ao desmatamento ilegal na Amazônia* (Amazonia 2030, 29 pp.). https://amazonia2030.org.br/wp-content/uploads/2022/03/AMZ2030_30.pdf. Accessed 26 November 2024

Negret PJ, Sonter L, Watson JEM, Possingham HP, Jones KR et al (2019) Emerging evidence that armed conflict and coca cultivation influence deforestation patterns. *Biological Conservation, 239*, e108176. https://doi.org/10.1016/j.biocon.2019.07.021

Nobre CA, Sampaio G, Borma LS, Castilla-Rubio JC, Silva JS et al (2016a) The Fate of the Amazon Forests: Land-use and climate change risks and the need of a novel sustainable development paradigm. *Proceedings of the National Academy of Science USA*, *113*, 10759–10768. https://doi.org/10.1073/pnas.1605516113

Nobre CA, Marengo JA, Seluchi ME, Cuartas LA, Alves LM (2016b) Some characteristics and impacts of the drought and water crisis in Southeastern Brazil during 2014 and 2015. *Journal of Water Resource and Protection, 8*(2)*,* 252-262. https://doi.org/10.4236/jwarp.2016.82022

Nogueira EM, Yanai AM, Fonseca FOR, Fearnside PM (2015) Carbon stock loss from deforestation through 2013 in Brazilian Amazonia. *Global Change Biology*, *21*, 1271–1292. https://doi.org/10.1111/gcb.12798

Nogueira EM, Yanai AM, de Vasconcelos SS, Graça, PMLA, Fearnside PM (2018) Brazil's Amazonian protected areas as a bulwark against regional climate change. *Regional Environmental Change*, *18*(3), 573–579. https://doi.org/10.1007/s10113-017-1209-2

Nolte C, Agrawal A, Silvius KM, Soares-Filho BS (2013) Governance regime and location influence avoided deforestation success of protected areas in the Brazilian Amazon. *Proceedings of the National Academy of Sciences USA, 110*(13), 4956–4961. https://doi.org/10.1073/pnas.1214786110

Oreskes N, Shrader-Frechette K, Belitz K (1994) Verification, validation, and confirmation of numerical models in the earth sciences. *Science, 263*, 641–646. https://doi.org/10.1126/science.263.5147.641

Pacheco P (2024) *Estradas na Amazônia são tapete vermelho para desmatadores* (Observatório do Clima). https://www.oc.eco.br/estradas-na-amazonia-sao-tapete-vermelho-para-desmatadores/. Accessed 26 November 2024

Pontes F (2024) Após Amacro, agronegócio mira expansão de suas fronteiras para regiões intocadas da Amazônia. *Varadouro*, 2 April 2024. https://ovaradouro.com.br/fronteiras-da-devastacao/. Accessed 26 November 2024

Qin Y, Xiao X, Liu F, de Sa e Silva F, Shimabukuro Y et al (2023) Forest conservation in Indigenous territories and protected areas in the Brazilian Amazon. *Nature Sustainability, 6*(4), 295–305. https://doi.org/10.1038/s41893-022-01018-z

Ramos CJP, Graça PMLA, Fearnside PM (2018) Deforestation dynamics on an Amazonian peri-urban frontier: Simulating the influence of the Rio Negro Bridge in Manaus, Brazil. *Environmental Management, 62*(6), 1134–1149. https://doi.org/10.1007/s00267-018-1097-3

Rykiel EJ (1996) Testing ecological models: The meaning of validation. *Ecological Modelling, 90*(3), 229–244. https://doi.org/10.1016/0304-3800(95)00152-2

Sampaio G, Borma LS, Cardoso M, Alves LM, von Randow C et al (2018) Assessing the possible impacts of a 4 °c or higher warming in Amazonia. In: Nobre CA et al. (eds.), *Climate Change Risks in Brazil.* Springer, Amsterdam, The Netherlands. pp. 201-218. https://doi.org/10.1007/978-3-319-92881-4_8

Santos JL, Yanai AM, Graça PMLA, Correia FWS, Fearnside PM (2023) Amazon deforestation: Simulated impact of Brazil's proposed BR-319 highway project. *Environmental Monitoring and Assessment, 195*, 1217. https://doi.org/10.1007/s10661-023-11820-7

Soares-Filho BS, Coutinho CG, Lopes PC (2002) DINAMICA – A stochastic cellular automata model designed to simulate the landscape dynamics in an Amazonian colonization frontier. *Ecological Modelling, 54*(3), 217–235. https://doi.org/10.1016/S0304-3800(02)00059-5

Soares-Filho BS, Davis JL, Rajão R (2020) *Pavimentação da BR-319, a Rodovia do Desmatamento* (Nota técnica 11/2020-01 – Centro de Sensoriamento Remoto e Laboratório de Gestão de Serviços Ambientais, Universidade Federal de Minas Gerais, Belo Horizonte, MG, Brazil. https://csr.ufmg.br/csr/wp-content/uploads/2020/11/Nota_tecnica_112020-01_pavimentacao_BR_319.pdf

Soares-Filho BS, Nepstad DC, Curran LM, Cerqueira GC, Garcia RA et al (2006) Modelling conservation in the Amazon basin. *Nature, 440*, 520–523. https://doi.org/10.1038/nature04389

Soares-Filho BS, Alencar A, Nepstad D, Cerqueira G, Vera Diaz M del C et al (2004) Simulating the response of land-cover changes to road paving and governance along a major Amazon highway: The Santarém-Cuiabá corridor. *Global Change Biology, 10*(5), 745–764. https://doi.org/10.1111/j.1529-8817.2003.00769.x

Soares-Filho BS, Rodrigues HO, Costa WL (2009) *Modeling Environmental Dynamics with Dinamica EGO*. Centro de Sensoriamento Remoto, Universidade Federal de Minas Gerais, Belo Horizonte, MG, Brazil. https://csr.ufmg.br/dinamica/dokuwiki/doku.php?id=tutorial:start

Soares-Filho BS, Rodrigues H, Follador M (2013) A hybrid analytical-heuristic method for calibrating land-use change models. *Environmental Modelling and Software*, *43*, 80–87. https://doi.org/10.1016/j.envsoft.2013.01.010

Steffen W, Rockström J, Richardson K, Lenton TM, Folke C, Liverman D, Summerhayes CP, Barnosky AD, Cornell SE, Crucifix M, Donges JF, Fetzer I, Lade SJ, Scheffer M, Winkelmann R, Schellnhuber HJ (2018) Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences*, 115(33), 8252-8259. https://doi.org/10.1073/pnas.1810141115

SUDAM (2021) Zona de desenvolvimento sustentável dos Estados do Amazonas, Acre e Rondônia 2021-2027: documento referencial. Superintendência do Desenvolvimento da Amazônia. https://irp.cdn-website.com/06e645c5/files/uploaded/amacro.pdf. Accessed 19 August 2025

Trisos CH, Merow C, Pigot AL (2020) The projected timing of abrupt ecological disruption from climate change. *Nature*, *580*, 496–501. https://doi.org/10.1038/s41586-020-2189-9

van der Ent RJ, Savenije HHG, Schaefli B, Steele-Dunne SC (2010) Origin and fate of atmospheric moisture over continents. *Water Resources Research*, 46, W09525. https://doi.org/10.1029/2010WR009127

Yanai AM, Graça PMLA, Escada MIS, Ziccardi LG, Fearnside PM (2020) Deforestation dynamics in Brazil's Amazonian settlements: Effects of land-tenure concentration. *Journal of Environmental Management*, *268*, e110555. https://doi.org/10.1016/j.jenvman.2020.110555

Yanai AM, Graça PMLA, Ziccardi LG, Escada MIS, Fearnside PM (2022) Brazil's Amazonian deforestation: The role of landholdings in undesignated public lands. *Regional Environmental Change, 22*(Suppl 1), 62–66. https://doi.org/10.1007/s10113-022-01897-0

Yang Z, Dominguez F (2019) Investigating land surface effects on the moisture transport over South America with a moisture tagging model. *Journal of Climate, 2*, 6627-6644. https://doi.org/10.1175/JCLI-D-18-0700.1

Zemp DC, Schleussner CF, Barbosa HMJ, van der Ent RJ, Donges JF et al (2014) On the importance of cascading moisture recycling in South America. *Atmospheric Chemistry and Physics, 14*, 13337–13359. https://doi.org/10.5194/acp-14-13337-2014

Supplementary Online Material

Modeling the impact of planned highways on deforestation and illegal land occupation in a critical area of Brazilian Amazonia: The Trans-Purus region

Authors: Aurora Miho Yanai[1*], Marcos Antonio Isaac Júnior[1], Jonathas Nunes da Silva[2,3], Marcelo Augusto dos Santos Junior[4], Paulo Maurício Lima de Alencastro Graça[1], Philip Martin Fearnside[1]

Affiliations:
[1]Department of Environmental Dynamics, National Institute for Research in Amazonia (INPA); Av. André Araújo n° 2936, CEP 69067-375, Manaus, Amazonas, Brazil.
[2]Department of Chemistry, Federal University of Amazonas (UFAM); Av. General Rodrigo Octávio n° 6200, CEP 69080-900, Manaus, Amazonas, Brazil.
[3]Center for Analysis, Research and Technological Innovation Foundation (FUCAPI); Av. Governador Danilo de Matos Areosa n° 381, CEP 69075-351, Manaus, Amazonas, Brazil.
[4]National Institute for Space Research (INPE), Av. dos Astronautas n° 1758, CEP 12227-010, São José dos Campos, São Paulo, Brazil.

*Corresponding author. Email: yanai@inpa.gov.br

Email address: yanai@inpa.gov.br; maisaacjunior@gmail.com; jonathas.water@gmail.com; brasa.bio@gmail.com; pmlag@inpa.gov.br; pmfearn@inpa.gov.br

This file includes:

Table S1. Online Resource 1. Identification of planned highways with the assumed years of construction and of the emergence (increment) of new landholdings. 3

Figure S1, Online Resource 2. Flowchart of Trans-Purus model. 4

Table S2, Online Resource 3. Increment of landholdings in the business-as-usual scenario in terms of number and area (ha) per year. Values for the initial year (2022) represent cumulative landholdings up to 2021. 5

Table S3, Online Resource 4. Variables used for explaining spatial patterns of deforestation. Distance maps were calculated in Dinamica-EGO. 6

Table S4, Online Resource 5. Cramer test with values ≥ 0.50 showing dependence between the variables for each region and the type of landholding. Variables in red were deleted from the weights-of-evidence file. The “Trans-Purus and Juruá regions (business-as-usual scenario)” have weights-of-evidence calculated based on observed deforestation in the South and BR-319 regions merged together. 7

Figure S2, Online Resource 6. Fuzzy minimum similarity index using a constant decay function. Window sizes represent the number of pixels (1 pixel = 250 × 250 m or 6.25 ha) in a square window area. 8

Table S5, Online Resource 7. Parameters of annual deforestation rates used in the business-as-usual and baseline scenarios. 9

Table S6, Online Resource 8. Mean deforestation rates (i.e., transition rates: forest to deforestation) used in each region and in simulations where the deforestation equation was used. 10

Figure S3, Online Resource 9. Example of (A) acceleration factor and (B) simulated deforestation rates in the BR-319 region in the business-as-usual scenario from 2022 to 2070. 11

Table S7, Online Resource 10. Deforestation rates estimated from 2010 to 2021 (minimum and maximum). 11

Table S8, Online Resource 11. Cumulative deforestation in undesignated public forest in the initial year (2021) and in the simulated scenarios (2070). 12

Table S9, Online Resource 12. Cumulative deforestation in Indigenous lands in the initial year (2021) and in the simulated scenarios (2070). 13

Table S10, Online Resource 13. Cumulative deforestation in full-protection conservation units in the initial year (2021) and in the simulated scenarios (2070). 14

Table S11, Online Resource 14. Cumulative deforestation in sustainable-use conservation units in the initial year (2021) and in the simulated scenarios (2070). 15

Figure S4. Online Resource 15. Comparison of studies: (A) dos Santos Junior et al. (2018), where deforestation projected to 2100 is in orange; (B) Santos et al. (2023) with deforestation to 2100, and (C) this study with deforestation to 2070. For better visual comparison, the original figures for panels (A) and (B) were clipped to the area of planned highways in the Trans-Purus region. In panel (C) (this study), the forest both inside and outside of landholdings is in white. 16

Figure S5, Online Resource 16. Total deforestation and secondary roads in the Mapinguari National Park (PARNA) in the South region in the initial year (2021) and (B) in the business-as-usual scenario (2070). 17

Online Resource 17. Dynamics of simulated deforestation in protected areas. 18

Figure S6, Online Resource 18. Deforestation and an illegal road (ramal) in protected areas in (A) the initial landscape (2021) and in the simulated scenarios (2070), (B) Baseline scenario, and (C) Business-as-usual scenario. 19

References 20

Table S1, Online Resource 1. Identification of planned highways with the assumed years of construction and of the emergence (increment) of new landholdings.

Planned highway	Highway stretch (From / To)	Construction year	Year of landholding emergence
AM-366 (part1)	Boca do Acará (Madeira River) / Tapauá	2031	2028
AM-360	Novo Aripuanã municipal seat / BR-319	2035	2032
AM-356	Borba municipal seat / BR-319	2035	2032
AM-366 (part 2)	Tapauá municipal seat / AM-343	2036	2033
AM-343	Coari municipal seat / AM-366	2036	2033
AM-366 (part 3)	AM-343 / Tefé municipal seat	2040	2037
AM-366 (part 4)	Tefé municipal seat / Juruá municipal seat	2044	2041
BR-317	Boca do Acre municipal seat / Lábrea municipal seat	2050	2047
AM-175	Pauini municipal seat / BR-317	2050	2047
BR-230 (part 1)	Lábrea municipal seat / Boa Vista (Tapauá River)	2055	2052
BR-230 (part 2)	Boa Vista / AM-333	2060	2057
AM-333	BR-230 / Carauari municipal seat	2060	2057

Figure S1, Online Resource 2. Flowchart of Trans-Purus model.

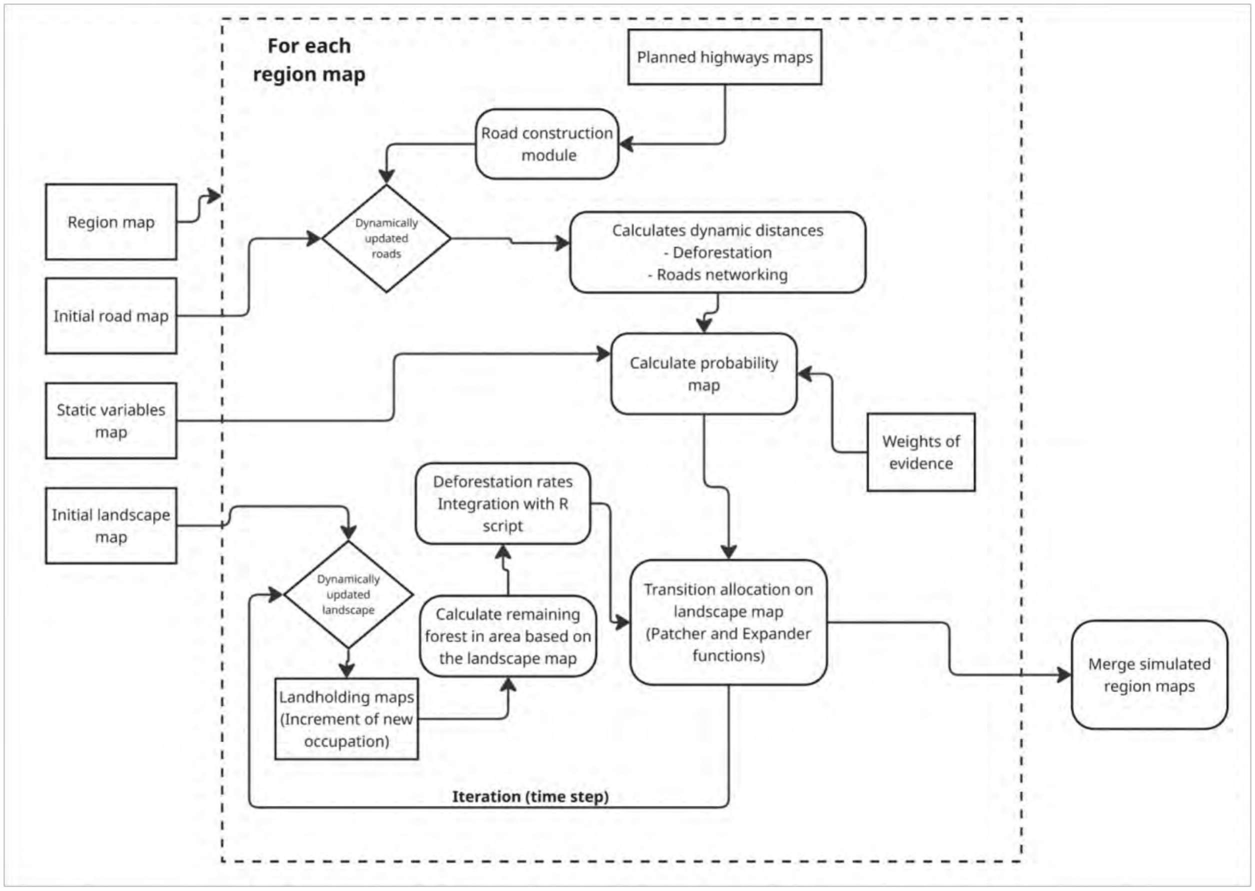

Table S2, Online Resource 3. Increment of landholdings in the business-as-usual scenario in terms of number and area (ha) per year. Values for the initial year (2022) represent cumulative landholdings up to 2021.

Year	Landholdings					
	≤100 ha		>100 ha		Total	
	Number	Area (km^2)	Number	Area (km^2)	Number	Area (km^2)
2022	12,929	5,821	5,382	56,449	18,311	62,270
2028	58	46	450	3,263	508	3,309
2031	101	114	101	1,430	202	1,544
2032	21	20	284	2,861	305	2,881
2033	24	5	106	1,386	130	1,391
2035	-	0	81	2,057	81	2,057
2037	27	25	199	1,340	226	1,365
2040	-	0	66	2,191	66	2,191
2041	86	82	150	2,663	236	2,745
2044	28	26	189	3,318	217	3,344
2047	50	30	265	3,898	315	3,928
2050	164	156	192	7,316	356	7,473
2052	52	49	75	4,920	127	4,969
2055	93	88	81	2,643	174	2,731
2057	228	182	279	3,903	507	4,085
2060	197	188	161	4,991	358	5,179
Total	**14,058**	**6,831**	**8,061**	**104,629**	**22,119**	**111,460**

Table S3, Online Resource 4. Variables used for explaining spatial patterns of deforestation. Distance maps were calculated in Dinamica-EGO.

Map	Description	Source
Distance to deforestation	Proximity to the nearest previously cleared area.	Amazon Deforestation Monitoring Project (PRODES)
Distance from highways, gas lines and secondary roads	Proximity to the nearest highway (e.g., BR-319), gas line (Urucu-Coari-Manaus) and secondary roads.	National Department of Transport Infrastructure (DNIT); Imazon and National Agency of Petroleum, Natural Gas, and Biofuels (ANP)
Distance from rivers	Proximity to the nearest river.	Amazon Deforestation Monitoring Project (PRODES)
Protected areas	Protected area categories: Indigenous Lands, full-protection and sustainable-use conservation units.	Ministry of Environment and Climate Change (MMAMC) and National Foundation for Indigenous Peoples (FUNAI)
Settlement projects	Settlement project categories: traditional settlements and environmentally distinctive settlements.	National Institute for Colonization and Agrarian Reform (INCRA)
Undesignated public forests	Federal and state untitled lands with no type of protection or a specific use attributed to them.	Brazilian Forest Service (SFB)
Deforestation hotspot areas in the BR-319 and South regions	Specific areas with landholdings that had more deforestation in comparison to surrounding areas (Vila Realidade on the BR-319 and Ramal do Boi and Jequitibá in Lábrea municipality in the South region). This map was only used in the BR-319 and South regions.	Brazilian Agriculture and Ranching Atlas (*Atlas da Agropecuária Brasileira*) from Imaflora

Table S4, Online Resource 5. Cramer test with values ≥ 0.50 showing dependence between the variables for each region and the type of landholding. Variables in red were deleted from the weights-of-evidence file. The "Trans-Purus and Juruá regions (business-as-usual scenario)" have weights-of-evidence calculated based on observed deforestation in the South and BR-319 regions merged together.

Region	Landholding category	First variable	Second variable	Cramer
Trans-Purus	Unknown	Distance from secondary roads	Protected areas	0.52
Manaus influence	≤100 ha	Distance from highways and gas lines	Settlement projects	0.55
	>100 ha	Distance from highways and gas line	Settlement projects	0.52
Juruá	>100 ha	Distance from secondary roads	Protected areas	0.64
	Unknown	Distance from secondary roads	Protected areas	0.64
South	≤100 ha	Distance from rivers	Settlement projects	0.88
		Undesignated public forests	Settlement projects	0.77
		Distance from highways and gas lines	Settlement projects	0.60
		Distance from secondary roads	Settlement projects	0.69
		Deforestation hotspot in BR-319 and South regions	Settlement projects	0.54
	>100 ha	Distance from highways and gas line	Settlement projects	0.61
		Deforestation hotspot in BR-319 and South regions	Settlement projects	0.54
		Undesignated public forests	Settlement projects	0.77
		Distance from secondary roads	Settlement projects	0.70
		Distance from rivers	Settlement projects	0.88
	Unknown	Distance from rivers	Settlement projects	0.85
		Undesignated public forests	Settlement projects	0.77
		Distance from secondary roads	Settlement projects	0.69
		Distance to deforestation	Settlement projects	0.64
		Distance from highways and gas lines	Settlement projects	0.61

		Deforestation hotspot in BR-319 and South regions	Settlement projects	0.54
Trans-Purus and Juruá (business-as-usual scenario)	≤100 ha	Distance from rivers	Settlement projects	0.65
		Distance from highways and gas lines	Settlement projects	0.80
	>100 ha	Distance from highways and gas lines	Settlement projects	0.80
		Distance from rivers	Settlement projects	0.65

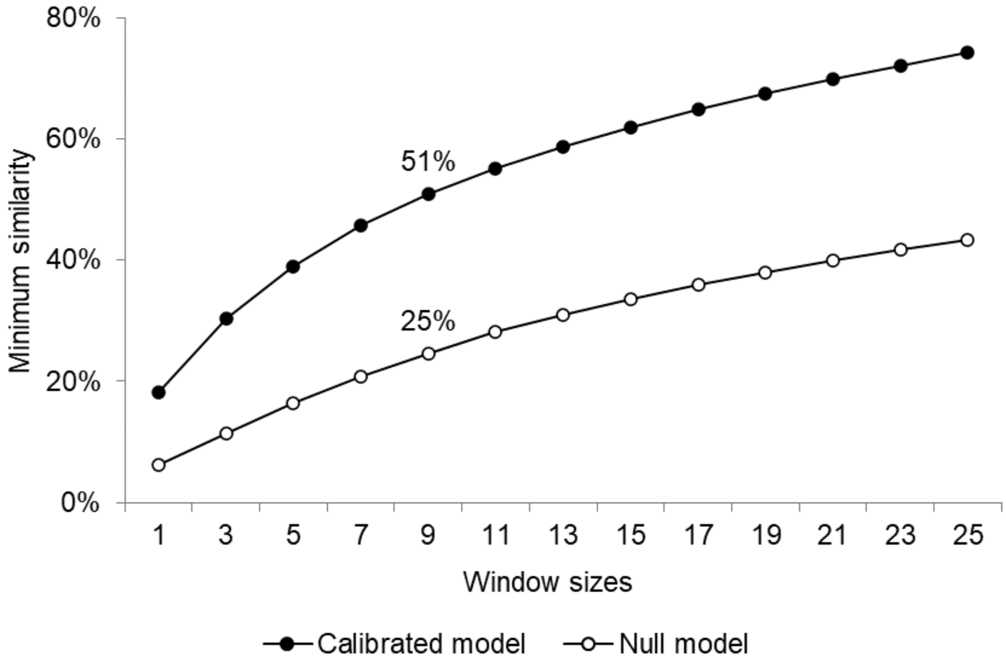

Figure S2, Online Resource 6. Fuzzy minimum similarity index using a constant decay function. Window sizes represent the number of pixels (1 pixel = 250 × 250 m or 6.25 ha) in a square window area.

Table S5, Online Resource 7. Parameters of annual deforestation rates used in the business-as-usual and baseline scenarios.

Region	Business-as-usual	Baseline
BR-319 and South	Estimated by the equation using a transition rate mean of recent trends with high rates (2016-2021) (Online Resource 7).	Estimated by the equation using a transition rate mean from the period 2010-2021 Online Resource 7)
Trans-Purus, Juruá	The year from the beginning of land occupation, the rates were estimated by the deforestation equation with the mean value estimated from the BR-319 and South regions rates (2016-2021) (Online Resource 7).	Based on the random selection of minimum and maximum values estimated from the transition rates (2010-2021) (Online Resource 9).
Manaus influence	Rates estimated by the equation with mean rates from the BR-319 region, which is the closest area (Online Resource 7).	

Table S6, Online Resource 8. Mean deforestation rates (i.e., transition rates: forest to deforestation) used in each region and in simulations where the deforestation equation was used.

Region	Simulation (steps and scenarios)	Landholdings	
		≤ 100 ha	**> 100 ha**
BR-319			
	Calibration (2010-2015)	0.001351	0.000586
	Validation (2016-2021)	0.012673	0.005947
	Baseline (2010-2021)	0.007012	0.003267
	Business-as-usual (2016-2021)	0.012673	0.005947
South			
	Calibration (2010-2015)	0.013884	0.003308
	Validation (2016-2021)	0.026993	0.014807
	Baseline (2010-2021)	0.020439	0.009057
	Business-as-usual (2016-2021)	0.026993	0.014807
Trans-Purus and Juruá			
	Business-as-usual: mean value from BR-319 and South regions (2016-2021)	0.019833	0.010377
Manaus influence			
	Business-as-usual: derived from BR-319 region (2016-2021)	0.012673	0.005947

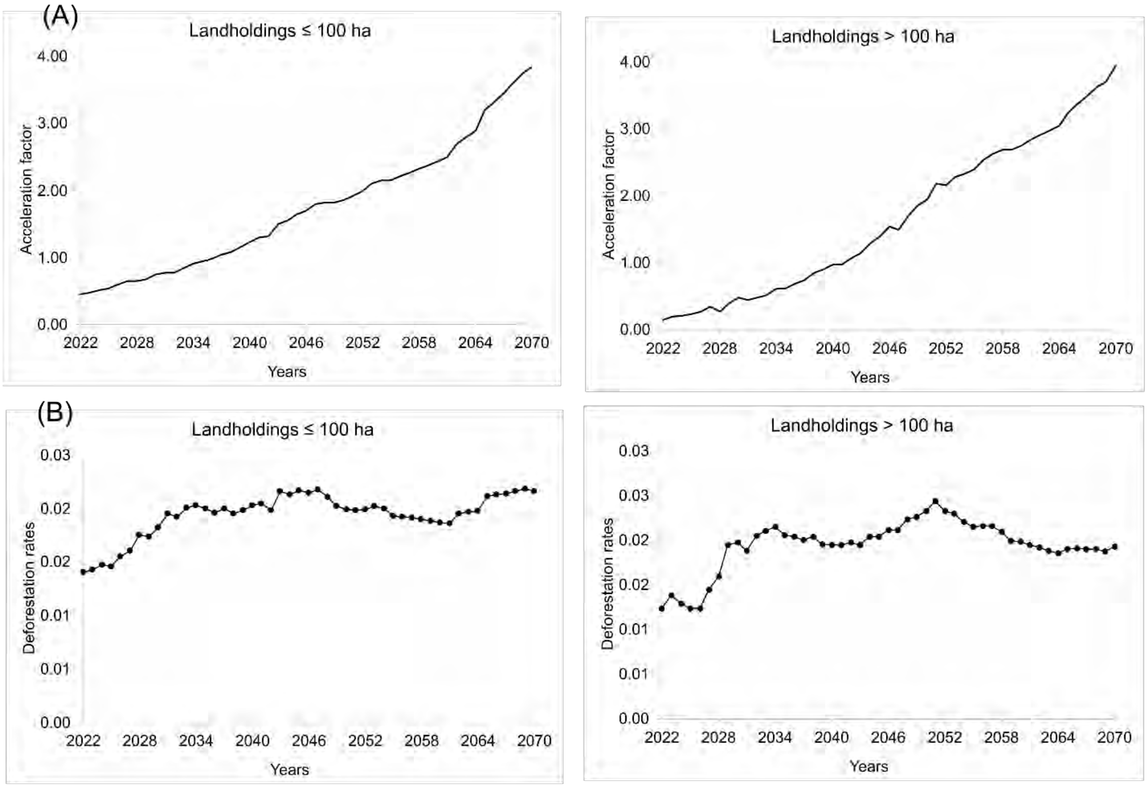

Figure S3, Online Resource 9. Example of (A) acceleration factor and (B) simulated deforestation rates in the BR-319 region in the business-as-usual scenario from 2022 to 2070.

Table S7, Online Resource 10. Deforestation rates estimated from 2010 to 2021 (minimum and maximum).

Region	Value	Category		
		≤ 100 ha	**> 100 ha**	**Unknown**
South	Min	-	-	0.00069
	Max	-	-	0.00438
BR-319	Min	-	-	0.00009
	Max	-	-	0.00100
Manaus influence	Min	0.00347	0.00151	0.00077
	Max	0.01505	0.01056	0.00301
Trans-Purus	Min	0.00225	0.00005	0.00004
	Max	0.01486	0.00029	0.00024
Juruá	Min	0	0	0.00002
	Max	0.00832	0.00120	0.00010

Table S8, Online Resource 11. Cumulative deforestation in undesignated public forest in the initial year (2021) and in the simulated scenarios (2070).

Scenario	Landholding category	Region (Area in km^2)					
		Trans-Purus	BR-319	Manaus influence	Juruá	South	Total
PRODES (2021)							
	≤ 100 ha	22	83	196	3	309	613
	> 100 ha	41	306	175	17	1,785	2,324
	Unknown	320	309	292	91	776	1,789
	All categories	382	699	663	112	2,870	4,725
Baseline (2070)							
	≤ 100 ha	80	175	502	7	690	1,453
	> 100 ha	127	1,186	481	26	6,667	8,488
	Unknown	1,120	1,480	1,082	201	3,065	6,948
	All categories	1,327	2,841	2,065	235	10,422	16,889
Business-as-usual (2070)							
	≤ 100 ha	463	267	554	16	849	2,148
	> 100 ha	15,221	5,233	1,570	1,189	7,512	30,725
	Unknown	1,027	1,051	891	202	3,096	6,267
	All categories	16,711	6,551	3,014	1,407	11,456	39,139

Table S9, Online Resource 12. Cumulative deforestation in Indigenous lands in the initial year (2021) and in the simulated scenarios (2070).

Scenario	Landholding category	Region (Area in km^2)					
		Trans-Purus	BR-319	Manaus influence	Juruá	South	Total
PRODES (2021)							
	≤ 100 ha	0	0	1	0	0	2
	> 100 ha	0	0	2	0	1	3
	Unknown	137	44	234	28	117	559
	All categories	137	44	237	28	118	564
Baseline (2070)							
	≤ 100 ha	0	0	2	0	0	2
	> 100 ha	0	0	2	0	1	3
	Unknown	138	60	462	28	149	837
	All categories	138	60	466	28	150	842
Business-as-usual (2070)							
	≤ 100 ha	0	0	2	0	0	2
	> 100 ha	2	0	3	0	1	5
	Unknown	139	136	422	28	152	876
	All categories	141	136	427	28	153	883

Table S10, Online Resource 13. Cumulative deforestation in full-protection conservation units in the initial year (2021) and in the simulated scenarios (2070).

Scenario	Landholding category	Region (Area in km^2)					
		Trans-Purus	BR-319	Manaus Influence	Juruá	South	Total
PRODES (2021)							
	≤ 100 ha	0	0	0	0	0	1
	> 100 ha	0	0	0	0	9	9
	Unknown	4	40	7	0	156	206
	All categories	4	40	7	0	165	215
Baseline (2070)							
	≤ 100 ha	0	0	0	0	1	1
	> 100 ha	0	0	0	0	17	17
	Unknown	4	81	7	0	2,797	2,889
	All categories	4	81	7	0	2,815	2,907
Business-as-usual (2070)							
	≤ 100 ha	0	5	0	0	1	6
	> 100 ha	0	12	0	0	29	41
	Unknown	5	74	7	0	2,559	2,644
	All categories	5	91	7	0	2,589	2,691

Table S11, Online Resource 14. Cumulative deforestation in sustainable-use conservation units in the initial year (2021) and in the simulated scenarios (2070).

Scenario	Landholding category	Region (Area in km^2)					
		Trans-Purus	BR-319	Manaus Influence	Juruá	South	Total
PRODES (2021)							
	≤ 100 ha	0	0	2	0	1	3
	> 100 ha	3	4	0	12	25	44
	Unknown	332	307	9	74	223	945
	All categories	335	311	11	86	249	992
Baseline (2070)							
	≤ 100 ha	0	0	2	0	3	4
	> 100 ha	4	24	2	12	123	165
	Unknown	421	560	35	78	714	1,808
	All categories	425	584	39	89	839	1,977
Business-as-usual (2070)							
	≤ 100 ha	652	8	2	14	15	690
	> 100 ha	0	2,724	3	139	3,417	6,282
	Unknown	433	514	32	75	680	1,734
	All categories	1,085	3,246	37	228	4,112	8,706

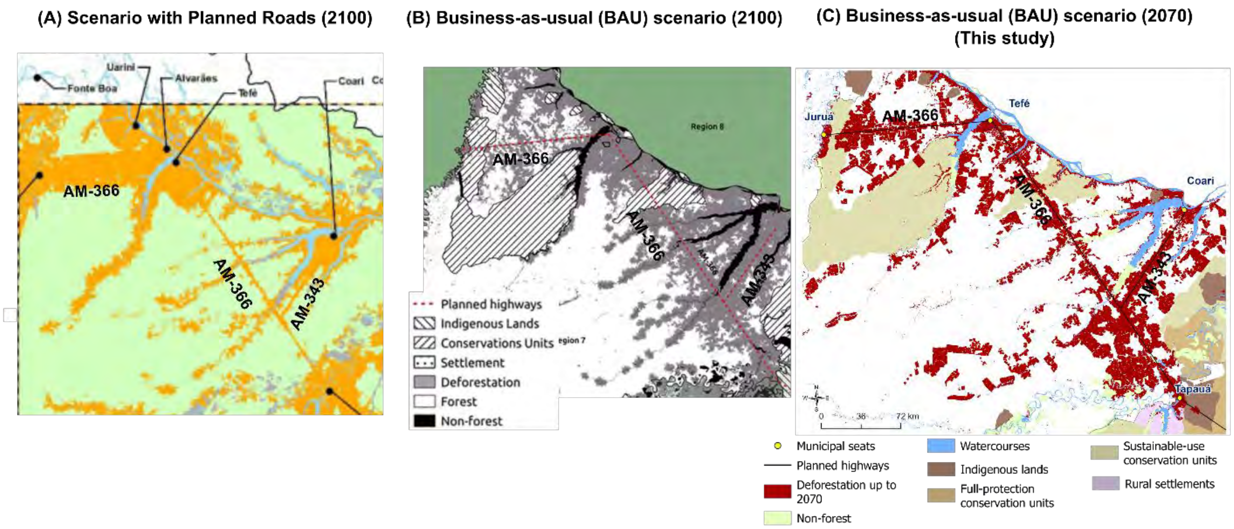

Figure S4, Online Resource 15. Comparison of studies: (A) dos Santos Junior et al. (2018), where deforestation projected to 2100 is in orange; (B) Santos et al. (2023) with deforestation to 2100, and (C) this study with deforestation to 2070. For better visual comparison, the original figures for panels (A) and (B) were clipped to the area of planned highways in the Trans-Purus region. In panel (C) (this study), the forest both inside and outside of landholdings is in white.

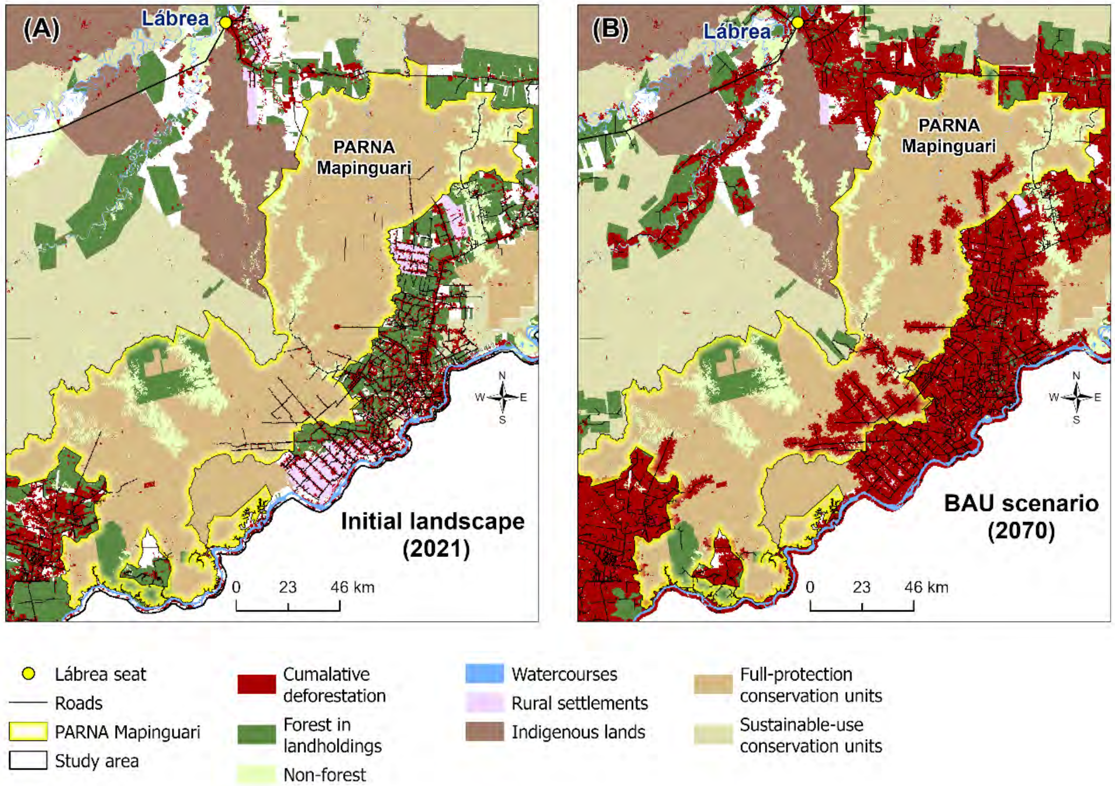

Figure S5, Online Resource 16. Total deforestation and secondary roads in the Mapinguari National Park (PARNA) in the South region in the initial year (2021) and (B) in the business-as-usual scenario (2070).

Online Resource 17. Dynamics of simulated deforestation in protected areas

The projected deforestation in the Indigenous lands was primarily represented by the "unknown" category because the data on landholdings (Imaflora 2021) used in our study considered land claims in conservation units but did not consider claims in Indigenous Lands. Although some overlap between Indigenous Lands and landholdings located on their edges existed, the chance of deforestation occurring in forest areas located in landholdings overlapping Indigenous Lands was, in general, low. However, in the BR-319 region, two Indigenous Lands (Apurinã Igarapé Tauamirim and Apurinã do Igarapé São João) exhibited an increase in deforestation in the business-as-usual scenario. These Indigenous Lands are located near the Tapauá municipal seat, and the initial segment of the AM-366 highway, connecting BR-319 highway to the Tapauá municipal seat, would follow the edge of the Apurinã do Igarapé São João Indigenous Land and completely traverse the Apurinã Igarapé Tauamirim Indigenous Land (**Online Resource 17**). These Indigenous Lands have already faced threats from illegal roads, logging and land conflicts with invaders (Fearnside et al. 2020; Ferrante et al. 2021). An illegal road (*ramal*) was identified in 2007 originating from the Tapauá municipal seat, skirting the first and passing through the second Indigenous Land and continuing into the Nascentes do Lago Jari National Park. This illegal road follows the route of the AM-366 highway (Fearnside et al. 2020).

Furthermore, we observed that the Mapinguari National Park (a full-protection conservation unit) had the largest percentage of the deforestation in this conservation-unit category (Figure S5). This protected area is among the ten most threatened in the Brazilian Amazon by illegal roads, with an estimated 978 km of roads built up to 2012 (Ribeiro et al, 2018). Areas near roads were highly attractive for deforestation in our simulation; hence, the projected deforestation was spatially distributed along these roads in the Mapinguari National Park. Deforestation in this protected area has substantially increased in recent years, with 129 ha cleared in 2019 and 934 ha cleared in 2022, representing a 624% increase (ISA 2024). Recent reports have also highlighted forest degradation (illegal logging and mining activities) in the park (Tudo Rondônia 2022). There were few landholdings with >100 ha in this area in the initial year (2021), and no significant deforestation was projected within these landholdings in this full-protection conservation unit, and there is no increment of landholdings in the business-as-usual simulation for this land category either.

In the South region, three sustainable-use conservation units (the Iquiri National Forest and the Ituxí and Médio Purus extractive reserves) face high deforestation pressure from outside areas, and the planned highway (BR-317) passing through the Iquiri State Forest and the Médio Juruá Extractive Reserve adds to the threat of deforestation and illegal land occupation. In the business-as-usual scenario, simulated landholdings allocated along the planned highway showed an increase in deforestation. Similar trends are expected to occur in the Lago do Capanã Grande Extractive Reserve, the Rio Amapá and Igapó-Açu sustainable development reserves, and the Tapauá State Forest along the BR-319 highway.

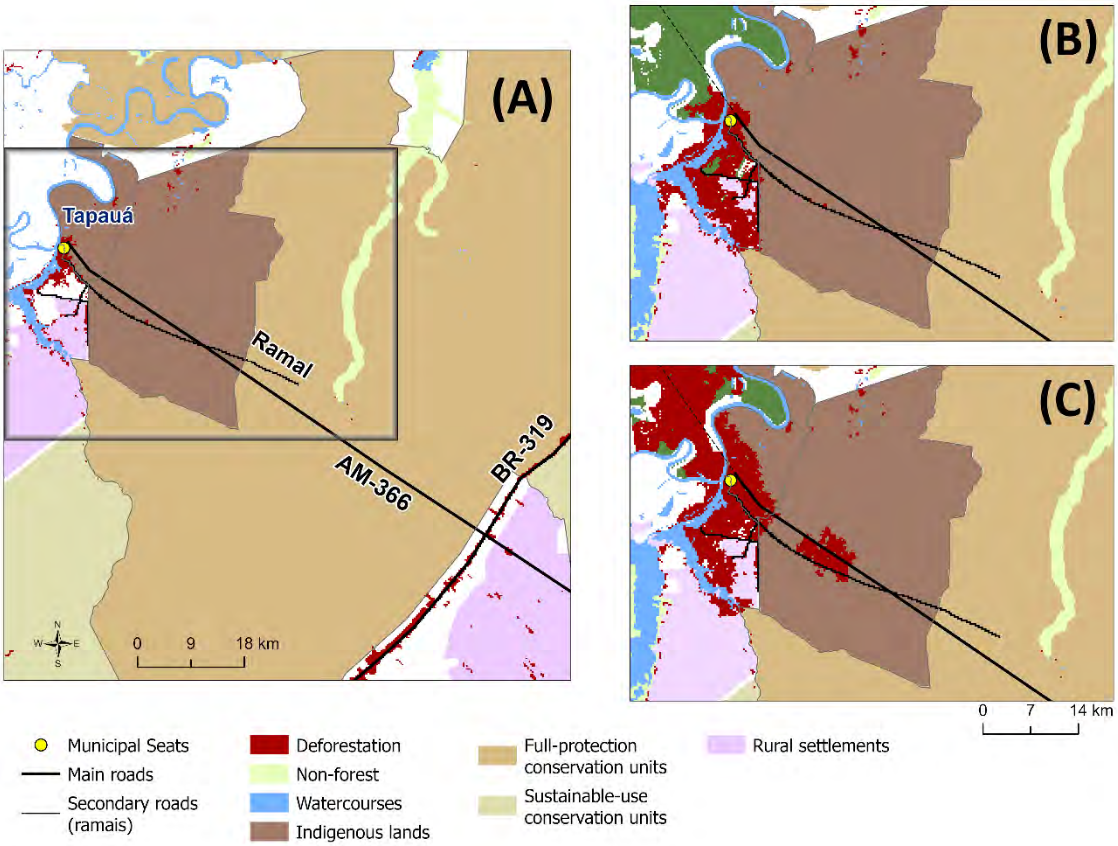

Figure S6, Online Resource 18. Deforestation and an illegal road (ramal) in protected areas in (A) the initial landscape (2021) and in the simulated scenarios (2070), (B) Baseline scenario, and (C) Business-as-usual scenario.

References

Fearnside PM, Ferrante L, Yanai AM, Isaac Júnior MA (2020, November 24) Trans-Purus: Brazil's last intact Amazon Forest at immediate risk (commentary). *Mongabay*. https://news.mongabay.com/2020/11/trans-purus-brazils-last-intact-amazon-forest-at-immediate-risk-commentary/. Accessed 6 January 2025

Ferrante L, Andrade MBT, Fearnside PM (2021) Land grabbing on Brazil's Highway BR-319 as a spearhead for Amazonian deforestation. *Land Use Policy, 108*, 105559. https://doi.org/10.1016/j.landusepol.2021.105559

Imaflora (Instituto de Manejo e Certificação Florestal e Agrícola) (2021) Malha fundiária da região norte do Brasil, V202105, Atlas da Agropecuária Brasileira. *Imaflora*. https://atlasagropecuario.imaflora.org/. Accessed 6 January 2025

ISA (Instituto Socio-Ambiental) (2024) Unidades de conservação no Brasil: Parque Nacional Mapinguari. *ISA, Programa de Monitoramento de Áreas Protegidas*. Instituto Socioambiental. https://nossosparques.org.br/arp/4968. Accessed 6 January 2025

Ribeiro J, Nunes S, Souza Jr. C (2018) Estradas não oficiais em áreas protegidas. *Instituto do Homem e Meio Ambiente da Amazônia (IMAZON)*. https://imazon.org.br/PDFimazon/Portugues/outros/OEstadoAPs_ESTRADAS.pdf. Accessed 6 January 2025

Tudo Rondônia (2022) PF deflagra operação de combate ao desmatamento do Parque Nacional do Mapinguari. *Tudo Rondônia*. https://www.tudorondonia.com/noticias/pf-deflagra-operacao-de-combate-ao-desmatamento-do-parque-nacional-do-mapinguari,88155.shtml. Accessed 6 January 2025

Supplementary Online Material

Modeling the impact of planned highways on deforestation and illegal land occupation in a critical area of Brazilian Amazonia: The Trans-Purus region

Authors: Aurora Miho Yanai[1*], Marcos Antonio Isaac Júnior[1], Jonathas Nunes da Silva[2,3], Marcelo Augusto dos Santos Junior[4], Paulo Maurício Lima de Alencastro Graça[1], Philip Martin Fearnside[1]

Affiliations:
[1]Department of Environmental Dynamics, National Institute for Research in Amazonia (INPA); Av. André Araújo n° 2936, CEP 69067-375, Manaus, Amazonas, Brazil.
[2]Department of Chemistry, Federal University of Amazonas (UFAM); Av. General Rodrigo Octávio n° 6200, CEP 69080-900, Manaus, Amazonas, Brazil.
[3]Center for Analysis, Research and Technological Innovation Foundation (FUCAPI); Av. Governador Danilo de Matos Areosa n° 381, CEP 69075-351, Manaus, Amazonas, Brazil.
[4]National Institute for Space Research (INPE), Av. dos Astronautas n° 1758, CEP 12227-010, São José dos Campos, São Paulo, Brazil.

*Corresponding author. Email: yanai@inpa.gov.br

Email address: yanai@inpa.gov.br; maisaacjunior@gmail.com; jonathas.water@gmail.com; brasa.bio@gmail.com; pmlag@inpa.gov.br; pmfearn@inpa.gov.br

This file includes:

Table S1. Online Resource 1. Identification of planned highways with the assumed years of construction and of the emergence (increment) of new landholdings. 3

Figure S1, Online Resource 2. Flowchart of Trans-Purus model. 4

Table S2, Online Resource 3. Increment of landholdings in the business-as-usual scenario in terms of number and area (ha) per year. Values for the initial year (2022) represent cumulative landholdings up to 2021. 5

Table S3, Online Resource 4. Variables used for explaining spatial patterns of deforestation. Distance maps were calculated in Dinamica-EGO. 6

Table S4, Online Resource 5. Cramer test with values ≥ 0.50 showing dependence between the variables for each region and the type of landholding. Variables in red were deleted from the weights-of-evidence file. The “Trans-Purus and Juruá regions (business-as-usual scenario)” have weights-of-evidence calculated based on observed deforestation in the South and BR-319 regions merged together. 7

Figure S2, Online Resource 6. Fuzzy minimum similarity index using a constant decay function. Window sizes represent the number of pixels (1 pixel = 250 × 250 m or 6.25 ha) in a square window area. ... 8

Table S5, Online Resource 7. Parameters of annual deforestation rates used in the business-as-usual and baseline scenarios. ... 9

Table S6, Online Resource 8. Mean deforestation rates (i.e., transition rates: forest to deforestation) used in each region and in simulations where the deforestation equation was used. ... 10

Figure S3, Online Resource 9. Example of (A) acceleration factor and (B) simulated deforestation rates in the BR-319 region in the business-as-usual scenario from 2022 to 2070. . 11

Table S7, Online Resource 10. Deforestation rates estimated from 2010 to 2021 (minimum and maximum). ... 11

Table S8, Online Resource 11. Cumulative deforestation in undesignated public forest in the initial year (2021) and in the simulated scenarios (2070). ... 12

Table S9, Online Resource 12. Cumulative deforestation in Indigenous lands in the initial year (2021) and in the simulated scenarios (2070). ... 13

Table S10, Online Resource 13. Cumulative deforestation in full-protection conservation units in the initial year (2021) and in the simulated scenarios (2070). ... 14

Table S11, Online Resource 14. Cumulative deforestation in sustainable-use conservation units in the initial year (2021) and in the simulated scenarios (2070). ... 15

Figure S4. Online Resource 15. Comparison of studies: (A) dos Santos Junior et al. (2018), where deforestation projected to 2100 is in orange; (B) Santos et al. (2023) with deforestation to 2100, and (C) this study with deforestation to 2070. For better visual comparison, the original figures for panels (A) and (B) were clipped to the area of planned highways in the Trans-Purus region. In panel (C) (this study), the forest both inside and outside of landholdings is in white. 16

Figure S5, Online Resource 16. Total deforestation and secondary roads in the Mapinguari National Park (PARNA) in the South region in the initial year (2021) and (B) in the business-as-usual scenario (2070). ... 17

Online Resource 17. Dynamics of simulated deforestation in protected areas ... 18

Figure S6, Online Resource 18. Deforestation and an illegal road (ramal) in protected areas in (A) the initial landscape (2021) and in the simulated scenarios (2070), (B) Baseline scenario, and (C) Business-as-usual scenario. ... 19

References ... 20

Table S1, Online Resource 1. Identification of planned highways with the assumed years of construction and of the emergence (increment) of new landholdings.

Planned highway	Highway stretch (From / To)	Construction year	Year of landholding emergence
AM-366 (part1)	Boca do Acará (Madeira River) / Tapauá	2031	2028
AM-360	Novo Aripuanã municipal seat / BR-319	2035	2032
AM-356	Borba municipal seat / BR-319	2035	2032
AM-366 (part 2)	Tapauá municipal seat / AM-343	2036	2033
AM-343	Coari municipal seat / AM-366	2036	2033
AM-366 (part 3)	AM-343 / Tefé municipal seat	2040	2037
AM-366 (part 4)	Tefé municipal seat / Juruá municipal seat	2044	2041
BR-317	Boca do Acre municipal seat / Lábrea municipal seat	2050	2047
AM-175	Pauini municipal seat / BR-317	2050	2047
BR-230 (part 1)	Lábrea municipal seat / Boa Vista (Tapauá River)	2055	2052
BR-230 (part 2)	Boa Vista / AM-333	2060	2057
AM-333	BR-230 / Carauari municipal seat	2060	2057

Figure S1, Online Resource 2. Flowchart of Trans-Purus model.

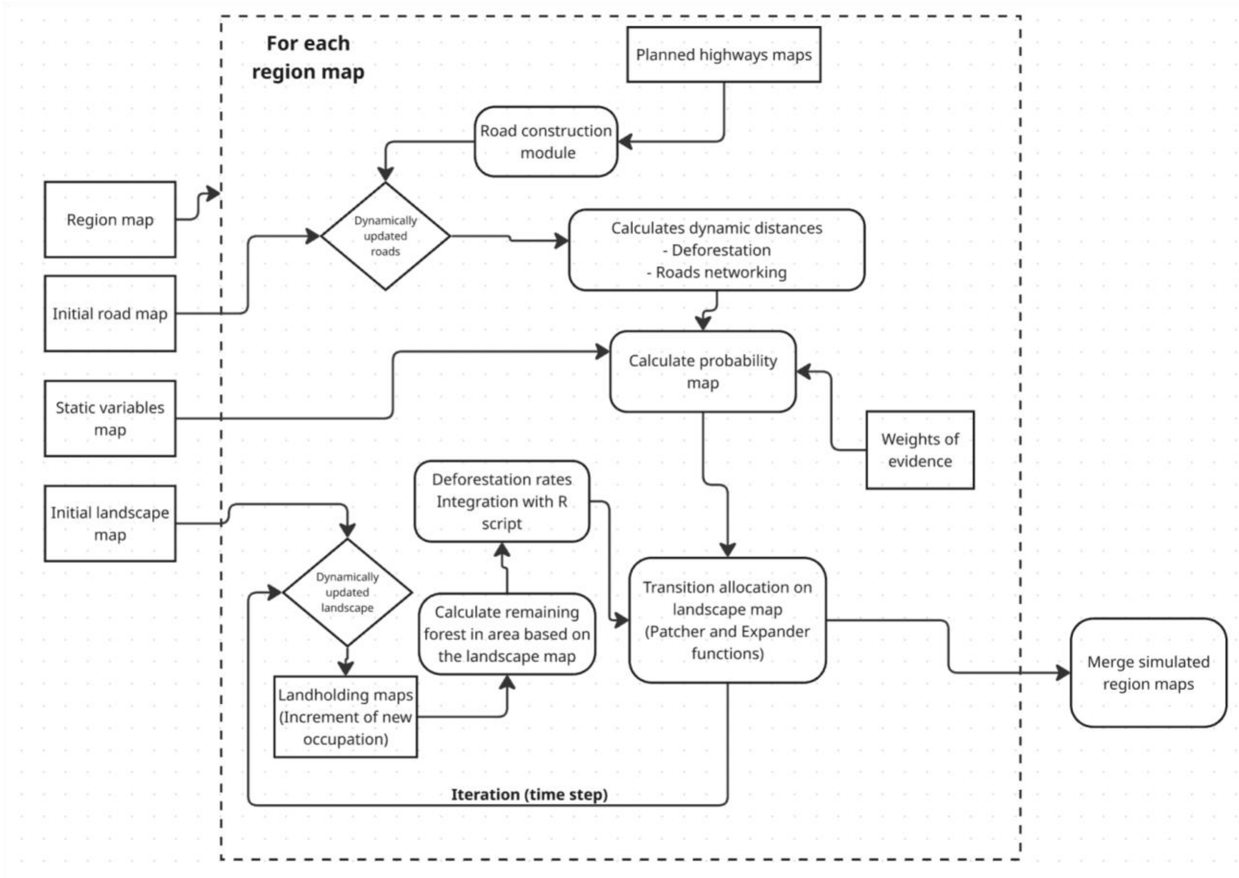

Table S2, Online Resource 3. Increment of landholdings in the business-as-usual scenario in terms of number and area (ha) per year. Values for the initial year (2022) represent cumulative landholdings up to 2021.

Year	**Landholdings**					
	≤100 ha		**>100 ha**		**Total**	
	Number	Area (km^2)	Number	Area (km^2)	Number	Area (km^2)
2022	12,929	5,821	5,382	56,449	18,311	62,270
2028	58	46	450	3,263	508	3,309
2031	101	114	101	1,430	202	1,544
2032	21	20	284	2,861	305	2,881
2033	24	5	106	1,386	130	1,391
2035	-	0	81	2,057	81	2,057
2037	27	25	199	1,340	226	1,365
2040	-	0	66	2,191	66	2,191
2041	86	82	150	2,663	236	2,745
2044	28	26	189	3,318	217	3,344
2047	50	30	265	3,898	315	3,928
2050	164	156	192	7,316	356	7,473
2052	52	49	75	4,920	127	4,969
2055	93	88	81	2,643	174	2,731
2057	228	182	279	3,903	507	4,085
2060	197	188	161	4,991	358	5,179
Total	**14,058**	**6,831**	**8,061**	**104,629**	**22,119**	**111,460**

Table S3, Online Resource 4. Variables used for explaining spatial patterns of deforestation. Distance maps were calculated in Dinamica-EGO.

Map	Description	Source
Distance to deforestation	Proximity to the nearest previously cleared area.	Amazon Deforestation Monitoring Project (PRODES)
Distance from highways, gas lines and secondary roads	Proximity to the nearest highway (e.g., BR-319), gas line (Urucu-Coari-Manaus) and secondary roads.	National Department of Transport Infrastructure (DNIT); Imazon and National Agency of Petroleum, Natural Gas, and Biofuels (ANP)
Distance from rivers	Proximity to the nearest river.	Amazon Deforestation Monitoring Project (PRODES)
Protected areas	Protected area categories: Indigenous Lands, full-protection and sustainable-use conservation units.	Ministry of Environment and Climate Change (MMAMC) and National Foundation for Indigenous Peoples (FUNAI)
Settlement projects	Settlement project categories: traditional settlements and environmentally distinctive settlements.	National Institute for Colonization and Agrarian Reform (INCRA)
Undesignated public forests	Federal and state untitled lands with no type of protection or a specific use attributed to them.	Brazilian Forest Service (SFB)
Deforestation hotspot areas in the BR-319 and South regions	Specific areas with landholdings that had more deforestation in comparison to surrounding areas (Vila Realidade on the BR-319 and Ramal do Boi and Jequitibá in Lábrea municipality in the South region). This map was only used in the BR-319 and South regions.	Brazilian Agriculture and Ranching Atlas (*Atlas da Agropecuária Brasileira*) from Imaflora

Table S4, Online Resource 5. Cramer test with values ≥ 0.50 showing dependence between the variables for each region and the type of landholding. Variables in red were deleted from the weights-of-evidence file. The "Trans-Purus and Juruá regions (business-as-usual scenario)" have weights-of-evidence calculated based on observed deforestation in the South and BR-319 regions merged together.

Region	Landholding category	First variable	Second variable	Cramer
Trans-Purus	Unknown	Distance from secondary roads	Protected areas	0.52
Manaus influence	≤100 ha	Distance from highways and gas lines	Settlement projects	0.55
	>100 ha	Distance from highways and gas line	Settlement projects	0.52
Juruá	>100 ha	Distance from secondary roads	Protected areas	0.64
	Unknown	Distance from secondary roads	Protected areas	0.64
South	≤100 ha	Distance from rivers	Settlement projects	0.88
		Undesignated public forests	Settlement projects	0.77
		Distance from highways and gas lines	Settlement projects	0.60
		Distance from secondary roads	Settlement projects	0.69
		Deforestation hotspot in BR-319 and South regions	Settlement projects	0.54
	>100 ha	Distance from highways and gas line	Settlement projects	0.61
		Deforestation hotspot in BR-319 and South regions	Settlement projects	0.54
		Undesignated public forests	Settlement projects	0.77
		Distance from secondary roads	Settlement projects	0.70
		Distance from rivers	Settlement projects	0.88
	Unknown	Distance from rivers	Settlement projects	0.85
		Undesignated public forests	Settlement projects	0.77
		Distance from secondary roads	Settlement projects	0.69
		Distance to deforestation	Settlement projects	0.64
		Distance from highways and gas lines	Settlement projects	0.61

		Deforestation hotspot in BR-319 and South regions	Settlement projects	0.54
Trans-Purus and Juruá (business-as-usual scenario)	≤100 ha	Distance from rivers	Settlement projects	0.65
		Distance from highways and gas lines	Settlement projects	0.80
	>100 ha	Distance from highways and gas lines	Settlement projects	0.80
		Distance from rivers	Settlement projects	0.65

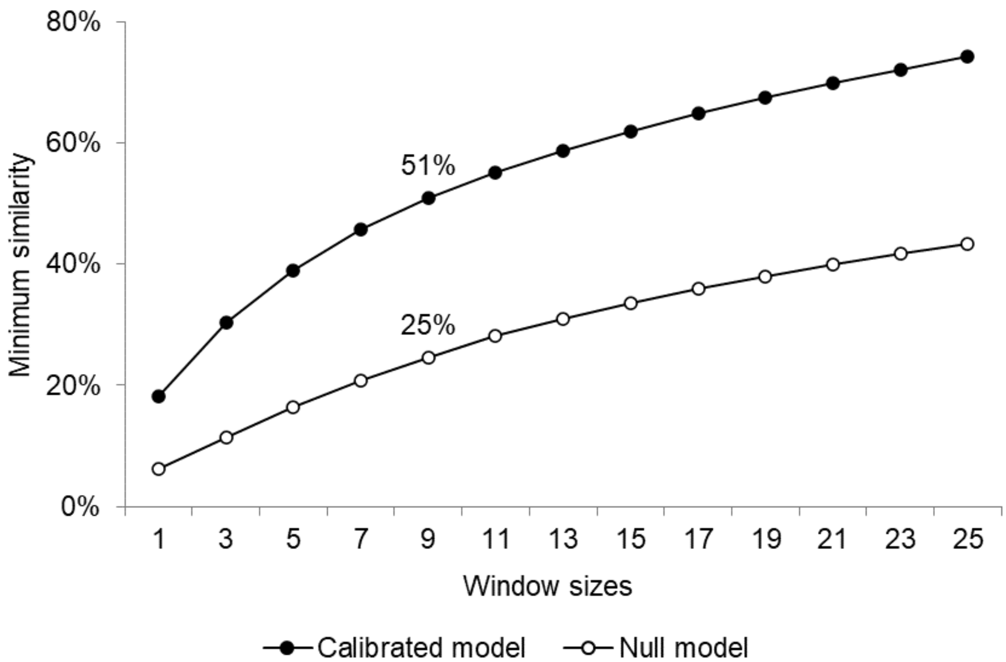

Figure S2, Online Resource 6. Fuzzy minimum similarity index using a constant decay function. Window sizes represent the number of pixels (1 pixel = 250 × 250 m or 6.25 ha) in a square window area.

Table S5, Online Resource 7. Parameters of annual deforestation rates used in the business-as-usual and baseline scenarios.

Region	Business-as-usual	Baseline
BR-319 and South	Estimated by the equation using a transition rate mean of recent trends with high rates (2016-2021) (Online Resource 7).	Estimated by the equation using a transition rate mean from the period 2010-2021 Online Resource 7)
Trans-Purus, Juruá	The year from the beginning of land occupation, the rates were estimated by the deforestation equation with the mean value estimated from the BR-319 and South regions rates (2016-2021) (Online Resource 7).	Based on the random selection of minimum and maximum values estimated from the transition rates (2010-2021) (Online Resource 9).
Manaus influence	Rates estimated by the equation with mean rates from the BR-319 region, which is the closest area (Online Resource 7).	

Table S6, Online Resource 8. Mean deforestation rates (i.e., transition rates: forest to deforestation) used in each region and in simulations where the deforestation equation was used.

Region	Simulation (steps and scenarios)	Landholdings	
		≤ 100 ha	> 100 ha
BR-319			
	Calibration (2010-2015)	0.001351	0.000586
	Validation (2016-2021)	0.012673	0.005947
	Baseline (2010-2021)	0.007012	0.003267
	Business-as-usual (2016-2021)	0.012673	0.005947
South			
	Calibration (2010-2015)	0.013884	0.003308
	Validation (2016-2021)	0.026993	0.014807
	Baseline (2010-2021)	0.020439	0.009057
	Business-as-usual (2016-2021)	0.026993	0.014807
Trans-Purus and Juruá			
	Business-as-usual: mean value from BR-319 and South regions (2016-2021)	0.019833	0.010377
Manaus influence			
	Business-as-usual: derived from BR-319 region (2016-2021)	0.012673	0.005947

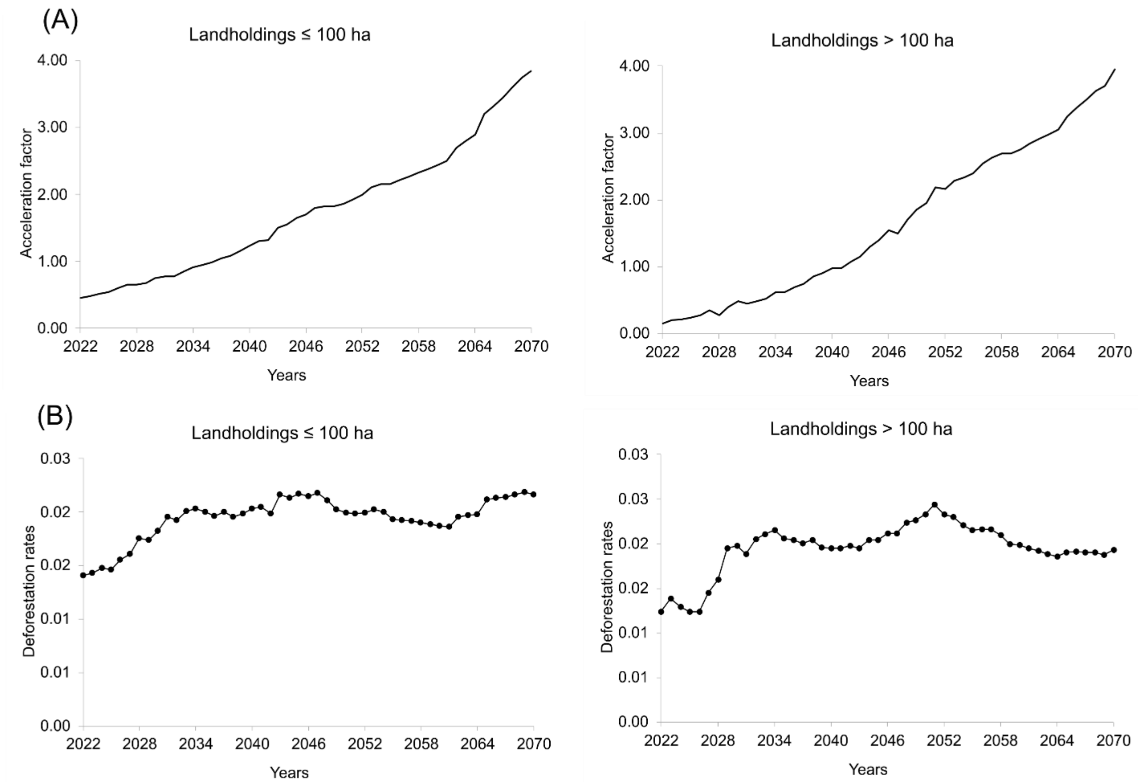

Figure S3, Online Resource 9. Example of (A) acceleration factor and (B) simulated deforestation rates in the BR-319 region in the business-as-usual scenario from 2022 to 2070.

Table S7, Online Resource 10. Deforestation rates estimated from 2010 to 2021 (minimum and maximum).

Region	Value	Category		
		≤ 100 ha	**> 100 ha**	**Unknown**
South	Min	-	-	0.00069
	Max	-	-	0.00438
BR-319	Min	-	-	0.00009
	Max	-	-	0.00100
Manaus influence	Min	0.00347	0.00151	0.00077
	Max	0.01505	0.01056	0.00301
Trans-Purus	Min	0.00225	0.00005	0.00004
	Max	0.01486	0.00029	0.00024
Juruá	Min	0	0	0.00002
	Max	0.00832	0.00120	0.00010

Table S8, Online Resource 11. Cumulative deforestation in undesignated public forest in the initial year (2021) and in the simulated scenarios (2070).

Scenario	Landholding category	Region (Area in km^2)					
		Trans-Purus	BR-319	Manaus influence	Juruá	South	Total
PRODES (2021)							
	≤ 100 ha	22	83	196	3	309	613
	> 100 ha	41	306	175	17	1,785	2,324
	Unknown	320	309	292	91	776	1,789
	All categories	382	699	663	112	2,870	4,725
Baseline (2070)							
	≤ 100 ha	80	175	502	7	690	1,453
	> 100 ha	127	1,186	481	26	6,667	8,488
	Unknown	1,120	1,480	1,082	201	3,065	6,948
	All categories	1,327	2,841	2,065	235	10,422	16,889
Business-as-usual (2070)							
	≤ 100 ha	463	267	554	16	849	2,148
	> 100 ha	15,221	5,233	1,570	1,189	7,512	30,725
	Unknown	1,027	1,051	891	202	3,096	6,267
	All categories	16,711	6,551	3,014	1,407	11,456	39,139

Table S9, Online Resource 12. Cumulative deforestation in Indigenous lands in the initial year (2021) and in the simulated scenarios (2070).

Scenario	Landholding category	Region (Area in km²)					
		Trans-Purus	**BR-319**	**Manaus influence**	**Juruá**	**South**	**Total**
PRODES (2021)							
	≤ 100 ha	0	0	1	0	0	2
	> 100 ha	0	0	2	0	1	3
	Unknown	137	44	234	28	117	559
	All categories	137	44	237	28	118	564
Baseline (2070)							
	≤ 100 ha	0	0	2	0	0	2
	> 100 ha	0	0	2	0	1	3
	Unknown	138	60	462	28	149	837
	All categories	138	60	466	28	150	842
Business-as-usual (2070)							
	≤ 100 ha	0	0	2	0	0	2
	> 100 ha	2	0	3	0	1	5
	Unknown	139	136	422	28	152	876
	All categories	141	136	427	28	153	883

Table S10, Online Resource 13. Cumulative deforestation in full-protection conservation units in the initial year (2021) and in the simulated scenarios (2070).

Scenario	Landholding category	Region (Area in km^2)					
		Trans-Purus	BR-319	Manaus Influence	Juruá	South	Total
PRODES (2021)							
	≤ 100 ha	0	0	0	0	0	1
	> 100 ha	0	0	0	0	9	9
	Unknown	4	40	7	0	156	206
	All categories	4	40	7	0	165	215
Baseline (2070)							
	≤ 100 ha	0	0	0	0	1	1
	> 100 ha	0	0	0	0	17	17
	Unknown	4	81	7	0	2,797	2,889
	All categories	4	81	7	0	2,815	2,907
Business-as-usual (2070)							
	≤ 100 ha	0	5	0	0	1	6
	> 100 ha	0	12	0	0	29	41
	Unknown	5	74	7	0	2,559	2,644
	All categories	5	91	7	0	2,589	2,691

Table S11, Online Resource 14. Cumulative deforestation in sustainable-use conservation units in the initial year (2021) and in the simulated scenarios (2070).

Scenario	Landholding category	Region (Area in km^2)					
		Trans-Purus	BR-319	Manaus Influence	Juruá	South	Total
PRODES (2021)							
	≤ 100 ha	0	0	2	0	1	3
	> 100 ha	3	4	0	12	25	44
	Unknown	332	307	9	74	223	945
	All categories	335	311	11	86	249	992
Baseline (2070)							
	≤ 100 ha	0	0	2	0	3	4
	> 100 ha	4	24	2	12	123	165
	Unknown	421	560	35	78	714	1,808
	All categories	425	584	39	89	839	1,977
Business-as-usual (2070)							
	≤ 100 ha	652	8	2	14	15	690
	> 100 ha	0	2,724	3	139	3,417	6,282
	Unknown	433	514	32	75	680	1,734
	All categories	1,085	3,246	37	228	4,112	8,706

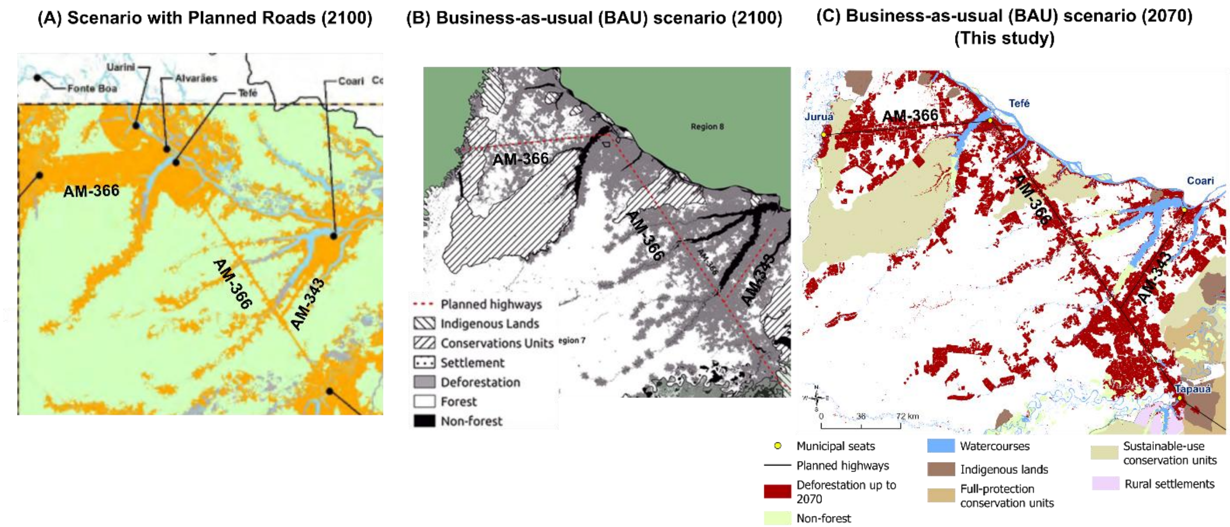

Figure S4, Online Resource 15. Comparison of studies: (A) dos Santos Junior et al. (2018), where deforestation projected to 2100 is in orange; (B) Santos et al. (2023) with deforestation to 2100, and (C) this study with deforestation to 2070. For better visual comparison, the original figures for panels (A) and (B) were clipped to the area of planned highways in the Trans-Purus region. In panel (C) (this study), the forest both inside and outside of landholdings is in white.

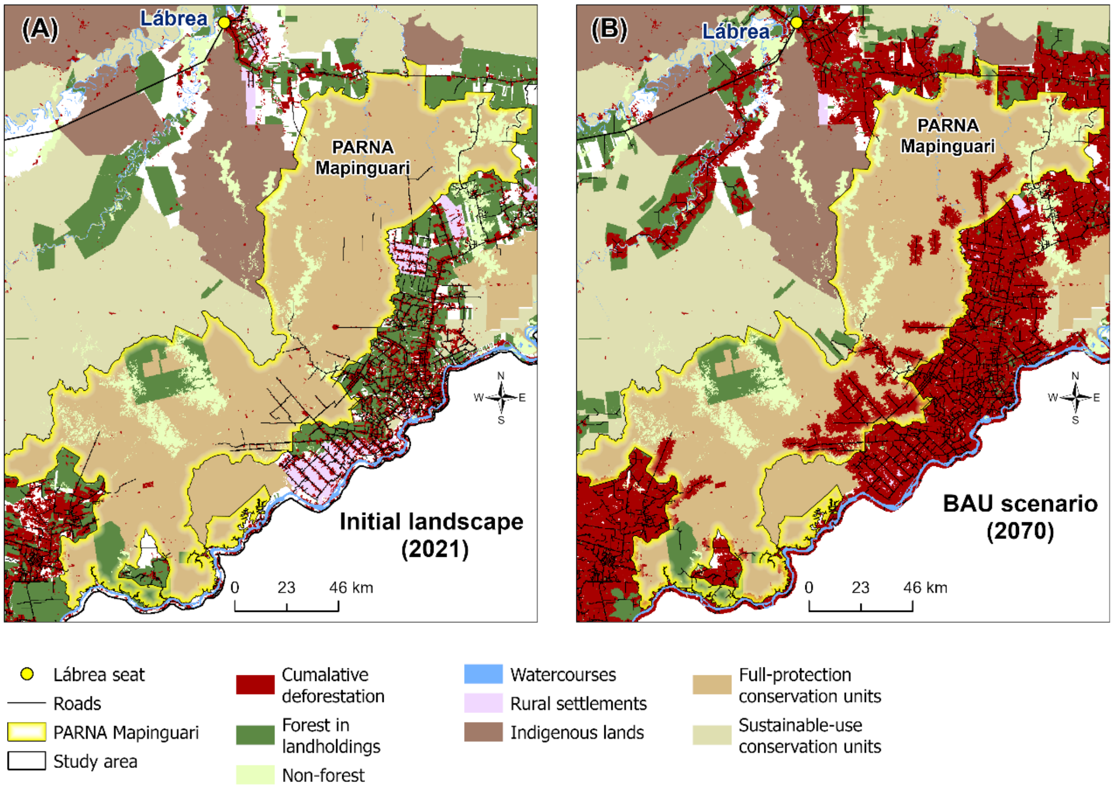

Figure S5, Online Resource 16. Total deforestation and secondary roads in the Mapinguari National Park (PARNA) in the South region in the initial year (2021) and (B) in the business-as-usual scenario (2070).

Online Resource 17. Dynamics of simulated deforestation in protected areas

The projected deforestation in the Indigenous lands was primarily represented by the "unknown" category because the data on landholdings (Imaflora 2021) used in our study considered land claims in conservation units but did not consider claims in Indigenous Lands. Although some overlap between Indigenous Lands and landholdings located on their edges existed, the chance of deforestation occurring in forest areas located in landholdings overlapping Indigenous Lands was, in general, low. However, in the BR-319 region, two Indigenous Lands (Apurinã Igarapé Tauamirim and Apurinã do Igarapé São João) exhibited an increase in deforestation in the business-as-usual scenario. These Indigenous Lands are located near the Tapauá municipal seat, and the initial segment of the AM-366 highway, connecting BR-319 highway to the Tapauá municipal seat, would follow the edge of the Apurinã do Igarapé São João Indigenous Land and completely traverse the Apurinã Igarapé Tauamirim Indigenous Land (**Online Resource 17**). These Indigenous Lands have already faced threats from illegal roads, logging and land conflicts with invaders (Fearnside et al. 2020; Ferrante et al. 2021). An illegal road (*ramal*) was identified in 2007 originating from the Tapauá municipal seat, skirting the first and passing through the second Indigenous Land and continuing into the Nascentes do Lago Jari National Park. This illegal road follows the route of the AM-366 highway (Fearnside et al. 2020).

Furthermore, we observed that the Mapinguari National Park (a full-protection conservation unit) had the largest percentage of the deforestation in this conservation-unit category (Figure S5). This protected area is among the ten most threatened in the Brazilian Amazon by illegal roads, with an estimated 978 km of roads built up to 2012 (Ribeiro et al, 2018). Areas near roads were highly attractive for deforestation in our simulation; hence, the projected deforestation was spatially distributed along these roads in the Mapinguari National Park. Deforestation in this protected area has substantially increased in recent years, with 129 ha cleared in 2019 and 934 ha cleared in 2022, representing a 624% increase (ISA 2024). Recent reports have also highlighted forest degradation (illegal logging and mining activities) in the park (Tudo Rondônia 2022). There were few landholdings with >100 ha in this area in the initial year (2021), and no significant deforestation was projected within these landholdings in this full-protection conservation unit, and there is no increment of landholdings in the business-as-usual simulation for this land category either.

In the South region, three sustainable-use conservation units (the Iquiri National Forest and the Ituxí and Médio Purus extractive reserves) face high deforestation pressure from outside areas, and the planned highway (BR-317) passing through the Iquiri State Forest and the Médio Juruá Extractive Reserve adds to the threat of deforestation and illegal land occupation. In the business-as-usual scenario, simulated landholdings allocated along the planned highway showed an increase in deforestation. Similar trends are expected to occur in the Lago do Capanã Grande Extractive Reserve, the Rio Amapá and Igapó-Açu sustainable development reserves, and the Tapauá State Forest along the BR-319 highway.

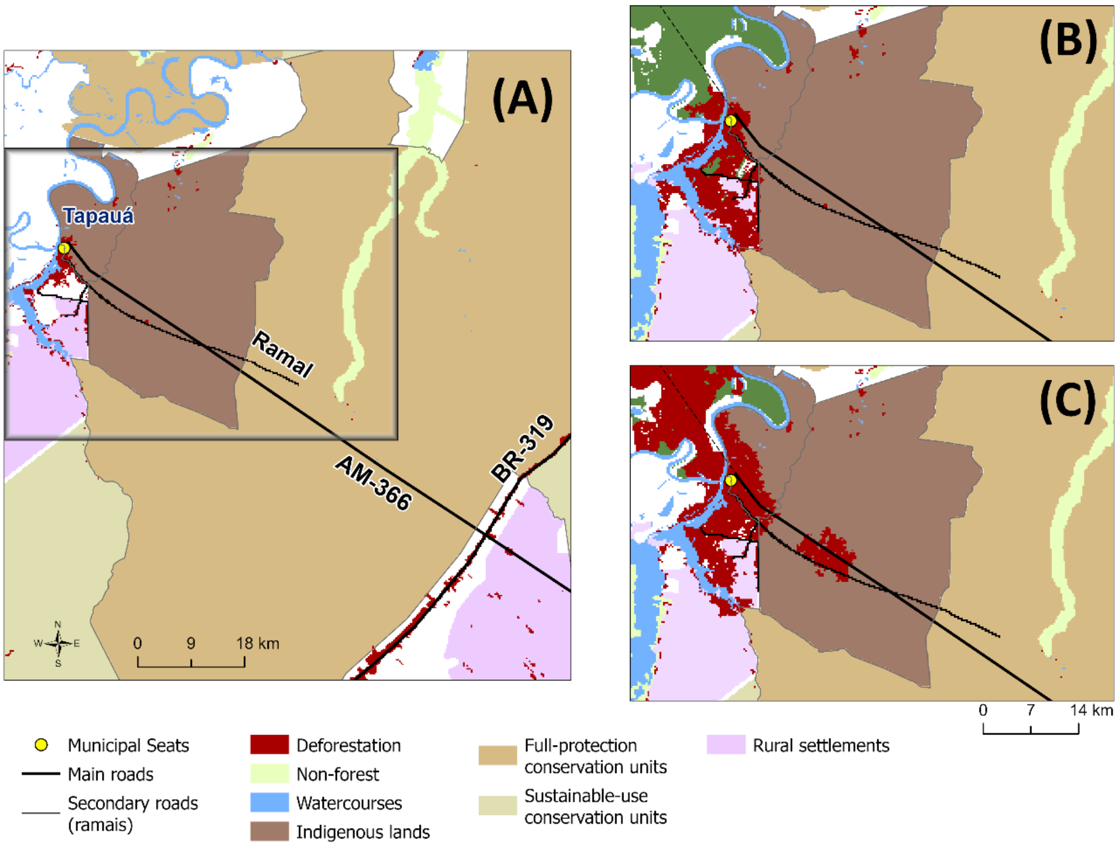

Figure S6, Online Resource 18. Deforestation and an illegal road (ramal) in protected areas in (A) the initial landscape (2021) and in the simulated scenarios (2070), (B) Baseline scenario, and (C) Business-as-usual scenario.

References

Fearnside PM, Ferrante L, Yanai AM, Isaac Júnior MA (2020, November 24) Trans-Purus: Brazil's last intact Amazon Forest at immediate risk (commentary). *Mongabay*. https://news.mongabay.com/2020/11/trans-purus-brazils-last-intact-amazon-forest-at-immediate-risk-commentary/. Accessed 6 January 2025

Ferrante L, Andrade MBT, Fearnside PM (2021) Land grabbing on Brazil's Highway BR-319 as a spearhead for Amazonian deforestation. *Land Use Policy, 108*, 105559. https://doi.org/10.1016/j.landusepol.2021.105559

Imaflora (Instituto de Manejo e Certificação Florestal e Agrícola) (2021) Malha fundiária da região norte do Brasil, V202105, Atlas da Agropecuária Brasileira. *Imaflora*. https://atlasagropecuario.imaflora.org/. Accessed 6 January 2025

ISA (Instituto Socio-Ambiental) (2024) Unidades de conservação no Brasil: Parque Nacional Mapinguari. *ISA, Programa de Monitoramento de Áreas Protegidas*. Instituto Socioambiental. https://nossosparques.org.br/arp/4968. Accessed 6 January 2025

Ribeiro J, Nunes S, Souza Jr. C (2018) Estradas não oficiais em áreas protegidas. *Instituto do Homem e Meio Ambiente da Amazônia (IMAZON)*. https://imazon.org.br/PDFimazon/Portugues/outros/OEstadoAPs_ESTRADAS.pdf. Accessed 6 January 2025

Tudo Rondônia (2022) PF deflagra operação de combate ao desmatamento do Parque Nacional do Mapinguari. *Tudo Rondônia*. https://www.tudorondonia.com/noticias/pf-deflagra-operacao-de-combate-ao-desmatamento-do-parque-nacional-do-mapinguari,88155.shtml. Accessed 6 January 2025