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Amazon deforestation: Simulated impact of Brazil's proposed BR-319 highway project

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Abstract

The scenario of deforestation in the Amazon may change with the reconstruction of the Highway BR-319, a long-distance road that will expand the region's agricultural frontier towards the north and west of the Western Amazon, stretches that until then have extensive areas of primary forest due to the hard access. We simulate the deforestation that would be caused by the reconstruction and paving of Highway BR-319 in Brazil’s state of Amazonas for the period from 2021 to 2100. The scenarios were based on the historical dynamics of deforestation in the state of Amazonas (business as usual, or BAU). Two deforestation scenarios were developed: a) BAU_1, where Highway BR-319 is not reconstructed, maintaining its current status and b) BAU_2, where the reconstruction and paving of the highway will take place in 2025, favoring the advance of the deforestation frontier to the northern and western portion of the state of Amazonas. In the scenario where the highway reconstruction is foreseen (BAU_2), the results show that deforestation increased by 60% by 2100 compared to the scenario without reconstruction (BAU_1), demonstrating that paving would increase deforestation beyond the limits of the highway's official buffer area (40 km). The study showed that protected areas (conservation units and indigenous lands) help to maintain forest cover in the Amazon region. At the same time, it shows how studies like this one can help in decision making.

Keywords: environmental modeling; land use change; Amazonia; arc of deforestation; human occupation.

Credit Author Statement

Author contributions

Jerfferson Lobato dos Santos: Conceptualization, Data curation, Calibration, Validation, Analysis, Writing, Original draft preparation.

Aurora Miho Yanai: Conceptualization, Methodology, Writing-Reviewing and Editing.

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1. INTRODUCTION

The Amazon basin covers an area of approximately 7 million km^2, with 5.5 million km^2 covered by forests, which represents 40% of the global tropical forest area (Nobre, 2014; Weng et al., 2018). Amazon ecosystems host 15-20% of the planet's species diversity (Lewinsohn & Prado, 2002) and store around 120 Gt of carbon (Saatchi et al., 2011). The Amazon rainforest plays an important role in the regional and global climate system through the storage and absorption of carbon (carbon cycle), transport of trace gases and aerosols, and through water cycling, which provides moisture that is transported to other regions of the continent, and contributes to maintaining the hydrological regime at regional and global scales (Rocha et al., 2015; Nobre et al., 2016; Marengo et al., 2018; Weng et al., 2018).

Deforestation, which is mostly for extensive cattle ranching, is a major contributor to greenhouse gas emissions and to climate change at both the regional and global scales (Fearnside et al., 2009; Moutinho, 2009; Marengo et al., 2018; Fearnside, 2022b). Deforestation in the Amazon has been monitored by satellite since 1988 and this monitoring is an important tool for guiding public policies aimed at controlling the destruction of forests in the region (INPE, 2020).

Deforestation in the Amazon is one of the major problems that Brazil has been facing in recent decades, and the reconstruction of highway BR-319 (Fig. 1a) is a major issue that has drawn the attention of environmentalists and researchers This highway would facilitate access to a large area of preserved forest, which could change the current scenario of deforestation in the Amazon (Fig. 1b) and cause substantial environmental and social impacts at the local, regional, and global levels.

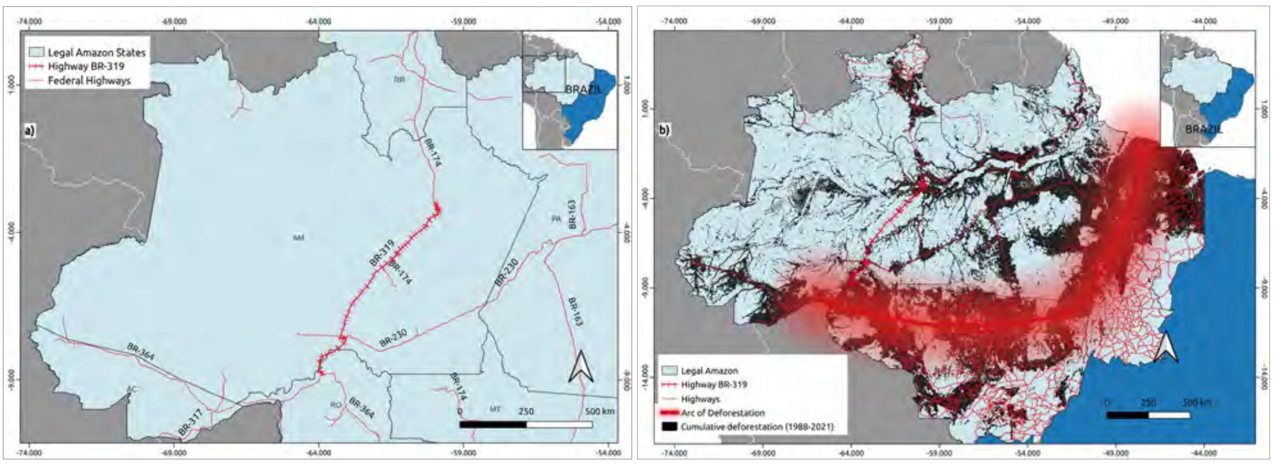


Fig. 1 a) Map of Highway BR-319, connecting the cities of Manaus, Amazonas and Porto Velho, Rondônia, showing the main federal highways. b) Official highways and the spatial distribution of cumulative deforestation (1988 to 2021) with emphasis on the 'arc of deforestation.' Map prepared by the authors. Data sources: IBGE, 2017; DNIT, 2021; INPE, 2020.

Highway BR-319 was built in 1972 and 1973 but was only inaugurated in 1976 (DNIT, 2016), a period of military government. The highway was part of Brazil's National Integration Program (PIN), under the motto "Security and

Development," uniting military concerns over perceived communist invasion with the developmental ideals promoted by President Juscelino Kubitschek in the 1950s (Lessa, 1991; Kohlhepp, 2002; Oliveira-Neto, 2014; Facundes, 2019). With the passage of time and lack of maintenance, the BR-319 became impassable in the late 1980s (DNIT, 2016) and its reconstruction became the focus of various local movements and governments (MPOG, 2004).

It was in the 1970s that the most critical period of changes in the Amazon landscape started in Brazil, when environmental impacts were intensified through colonization and development programs based on highways. These highways still have an important role in the occupation of space, attracting people in search of cheap land and natural resources and, consequently, increasing deforestation, fires, illegal logging, growth of cattle ranching, illegal mining, speculation and land grabbing, armed conflicts, and disease outbreaks, among other effects (Lessa, 1991; Loureiro, 2002; Fearnside, 2003; Graça et al., 2007; Laurance & Balmford, 2013; Brito & Castro, 2018).

Barber *et al*. (2014) showed that 94% of all deforestation in the Brazilian Amazon occurred around official and endogenous roads, demonstrating the role of highways as important drivers of deforestation. Reconstruction of Highway BR-319 is therefore the subject of growing concerns, as disorderly occupation and environmental degradation can extend the 'arc of deforestation' (Fig. 1b) advancing to the northern part of the state of Amazonas and to the state of Roraima, reaching the border with Venezuela via Highway BR-174 (Manaus - Boa Vista) (Fearnside et al., 2009; Fearnside & Graça, 2009; Barni et al., 2015). Planned roads associated with BR-319 would extend the impact to the western portion of the state of Amazonas (Fearnside, 2018).

Even so, many politicians and enthusiasts for the reconstruction of Highway BR-319 have claimed that deforestation would not occur, contrary to the warnings of scientists. However, it is a fact that the simple announcement of the paving and improvement plans has already resulted in a disorderly pattern of occupation and an increase in deforestation and fires along the middle stretch of the highway, with rampant illegal logging and invasion of public lands for real estate speculation and extensive cattle ranching (Fearnside & Graça, 2009; Andrade et al., 2021; Ferrante et al., 2021).

The situation is made more worrisome by the current Brazilian scenario in which there is a tendency for deforestation to increase, as can be seen in Fig. 2a. This trend is related to the economic pressures and political power of groups with interests in land-related businesses and infrastructure projects in the Amazon, which has led to the weakening of the Brazilian Forest Code (Supplementary Material, Appendix 1) and to other legislative changes that have been progressively eliminating restrictions on deforestation since 2012 (Fearnside, 2022a). The 2019-2022 Jair Bolsonaro presidential administration revoked many of the government's internal norms that had been established to combat deforestation (Barbosa et al., 2021). At least 401 of these changes can be reversed in 2023 by the incoming Luiz Inácio Lula da Silva administration (TALANOA, 2022). Legislative changes, however, will face a National Congress with a new composition, indicating that it will be even more hostile to environmental protection than the Congress during the Bolsonaro administration (ClimaInfo, 2022).

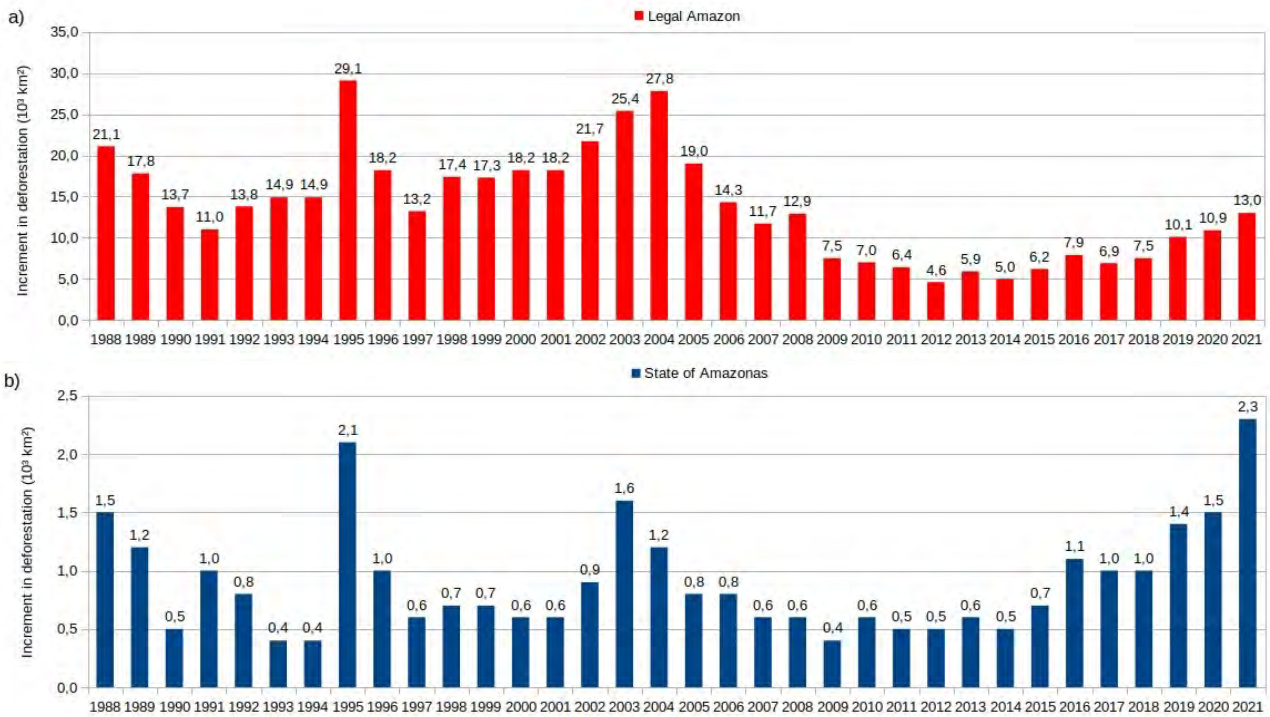


Fig. 2 Deforestation in the Brazilian Legal Amazon (a) and in the State of Amazonas (b) from 1988 to 2021 in 103 km^2. Source: INPE (2022).

According to data from the Project for Monitoring Deforestation in the Legal Amazon by Satellite (PRODES), of the National Institute for Space Research (INPE), the state of Amazonas resumed the increase of annual deforestation, from 523 km^2 in 2012 to 2306 km^2 in 2021, an increase of 440% (INPE, 2022), surpassing the historic record of 1995 (Fig. 2b). Furthermore, these data show that much of the deforestation in the state of Amazonas was concentrated in the southern part of the study area, which is under the direct influence of BR-230 (Transamazon Highway) and BR-364 (Porto Velho– Rio Branco).

Thus, given the possibility of the reconstruction and paving of BR-319 and the possible changes in the pattern of land use and cover, the question that the present study proposes to answer is: “What would be the impact of paving Highway BR-319 on deforestation in the state of Amazonas in 2050 and 2100?”. The present study aims to evaluate the impact of BR-319 and other highways planned in the study area.

2. MATERIAL AND METHODS

2.1. Study area

The study focuses on the federal highway BR-319, located in the interfluve between the Madeira and Purus Rivers, connecting the cities of Manaus (Amazonas) and Porto Velho (Rondônia). The BR-319 is the main land access route to the municipalities of Careiro, Manaquiri, Careiro da Várzea, and Autazes, as well as facilitating access to Humaitá, Lábrea, and Manicoré. It provides the only land access to the communities of Vila Realidade (district of the municipality of Humaitá) and Igapó-Açu (a district of the municipality of Borba). However, all of these locations are accessible from the two ends of the highway without reconstructing the critical “middle stretch” that would give access from the arc of deforestation to all areas connected to Manaus by road, including the state of Roraima.

The official road network in the state of Amazonas that connects to the 885 km of BR-319 corresponds to 1934 km, comprising the federal highways BR-230 (827 km from Lábrea to the border between the states of Amazonas and Pará), BR-174 (85 km, stretch BR-319 - Manicoré), and state highways AM-254 (94 km, BR-319 - Autazes) and AM-354 (43 km, BR-319 - Manaquiri). In addition, there are other planned projects by the government of the state of Amazonas to build highways connecting BR-319 to other municipalities such as Borba (AM-356), Novo Aripuanã (AM-360), Tapauá, Tefé and Juruá (AM-366) and Coari (AM-343). The last two roads (AM-366 and AM-343) would advance into the vast area of forest to the west of the Purus River, facilitating deforestation in one of the most preserved forest areas in Amazonia, known as the “Trans-Purus” region (Fearnside et al., 2020) (Fig. 3). Very little of the area that would be accessed by these connecting roads is protected by designation as a “conservation unit.” (Fig. 3).

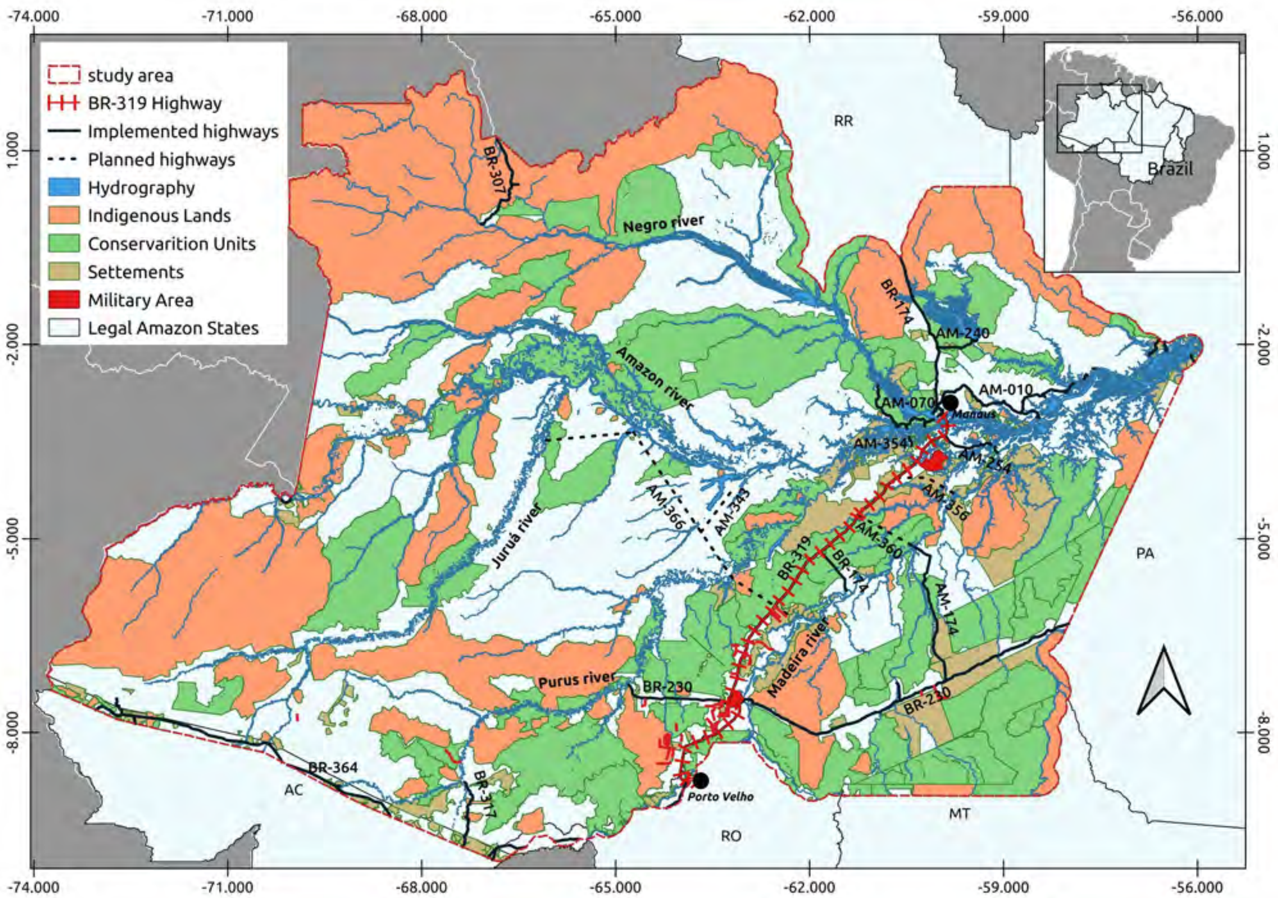


Fig. 3 Study area, Highway BR-319 and road network planned around BR-319, federal and state protected areas, indigenous lands, federal settlement projects and military areas. Map prepared by the authors. Data sources: IBGE (2017), ICMBio, INCRA, FUNAI.

The official area of influence used in Brazil's environmental licensing processes for highways in the Amazon region is 40 km of buffer area, defined by Interministerial Ordinance 60 of 24 March 2015 (Brazil, 2015). However, considering that the environmental impact of a paved highway in the Amazon can go beyond the minimum limit defined in the interministerial decree, the present study considered the state of Amazonas as the total area for modeling the impacts of deforestation, having as a 'backbone' Highway BR -319, as well as its connecting highways and roads, including both existing and planned roads. The study area also includes a buffer zone of 20 km around the borders of the state of Amazonas to represent the influence of adjacent areas, especially the highways present in the states of Acre, Rondônia, Roraima, and Pará (Fig. 3).

2.2. Land-Use Modeling

Modeling deforestation was done using the environmental modeling platform DINAMICA-EGO (Environment for Geoprocessing Objects) (Soares-Filho et al., 2002; Leite-Filho et al., 2020). DINAMICA-EGO can be applied to a variety of types of studies, such as urban expansion modeling, economic ecological zoning proposals, and the simulation of deforestation behavior (Soares-Filho et al., 2004; Rodrigues et al., 2007; Ramos et al., 2018; Santos et al., 2021). In addition, the software is open access and has a user-friendly interface, which can be used by people unfamiliar with programming languages such as R and Python. More details on the software can be found in the Supplementary Material (Appendix 2, Fig. S1).

2.3. Deforestation modeling steps

The modeling process was carried out through the following steps: input data, calibration, validation, and simulation (projection) of future deforestation. For the input and calibration data, the period from 2007 to 2013 was used. For validation, the period from 2014 to 2021 was used, while the simulation scenarios were for the period from 2021 to 2100.

2.3.1. Input data

All input cartographic data were in raster format with a spatial resolution of 100 m. The mapping used the *Brazil Policonic* Cartesian coordinate system, Datum SIRGAS 2000.

In addition to land-cover maps, maps of static and dynamic variables were used. Static variables are those for which the value of the class of each cell (pixel) does not change over the course of a simulation. For this category, maps of protected areas were used - indigenous lands (FUNAI, 2020), federal protected areas for integral protection and federal protected areas for sustainable use (ICMBio, 2019), state protected areas for integral protection and state protected areas for sustainable use (SEMA, 2021), and military areas (ANM, 2021). A map of settlement projects (INCRA, n.d) and official hydrography or watercourses (INPE, 2020) were also used.

Dynamic variables are those whose values change over the course of a simulation. These included distance from official and endogenous roads and distance from deforested areas. The Supplementary Material (Appendix 3) presents a summary of the variables used in the configurations (Table S1) and the map of static variables (Fig. S2).

2.3.1.1. **Regionalization of the study area**

The model applied in this study used the regionalization approach, which consists of establishing different parameters for each region and modeling the regional context that influences a given phenomenon (Leite-Filho et al., 2020). The software uses a set of functors (tools or small subroutines) to divide a map into parts (i.e., regions) to process the dataset of each region separately and then combine them. For this, a regionalized map of the study area was added as input to the model.

Thus, considering that the regionalization of the area makes it possible to individually parameterize each region, in the present study the area was divided into nine regions (Fig. 4) that took into account the presence of highways (current and planned), human clusters, land-use profile (contribution of social actors in deforestation) and hydrography. A summary of the parameters used to divide the study area into regions is provided in the Supplementary Material (Appendix 4, Table S2).

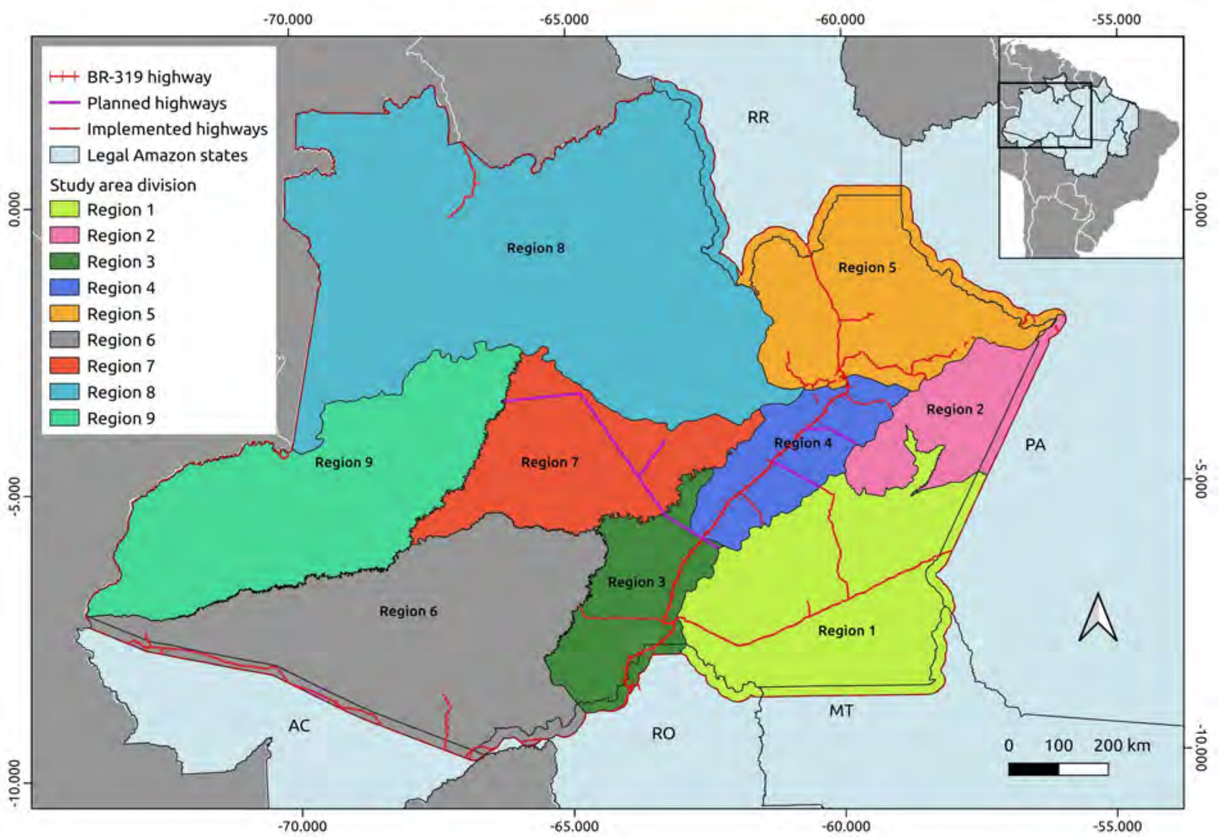


Fig. 4 Regionalized map of the study area.

2.3.2. Calibration

Calibration is the step of fitting the model parameters so that the simulation results are as similar as possible to the real study case (Campos et al., 2022). Therefore, in this phase there is a continuous search to adjust these parameters until the simulation result is as close as possible to the real one. In this study the reference period used to calibrate the model was from 2007 to 2013, with the goal of performing a validation simulation round for the period from 2014 to 2021, comparing the simulated map of 2021 with the satellite data for observed deforestation from the PRODES map for 2021.

Among the data needed to be applied in the simulation model are the weights of evidence of the variables, this being a measure of influence that each variable has to cause a change, in this case the expansion of deforestation (Leite-Filho et al., 2020). The weights-of-evidence applied in DINAMICA-EGO are based on a Bayesian method where the effect of a spatial variable is calculated independently of any combination to produce maps that describe the most-favorable areas for a change to occur (Soares-Filho et al., 2002, 2004; Leite-Filho et al., 2020).

To calculate the weights of evidence, a model was used in DINAMICA-EGO, which received the initial (2007) and final (2013) landscape maps, in addition to the maps of static and dynamic variables, followed by calculating the ranges and assigning transition-probability values for each variable used in the simulation model. An adjustment was necessary to achieve the desired result, by defining the interval and distance of the weights of evidence at 100 m and 1500 m, respectively, for the variables roads, deforestation, and hydrography. Such values were reached after several rounds of adjustments and the validation test indicated that the best result was in this influence range. The table of parameters used in the present study and a figure summarizing the calculation of the weights-of-evidence coefficients can be found in the Supplementary Material (Appendix 5, Table S3, Fig. S3).

Considering that the only assumption for the weights-of-evidence method is that the input maps be spatially independent, the next step is to analyze the correlation between the variable maps (Leite-Filho et al., 2020). After the analysis of correlated pairs between variables using the Cramer's test and joint-uncertainty information, values above 0.5 were considered as dependent variables (Bonham-Carter, 1994). No dependent variables were observed in the present study.

Another parameter used in the model is the transition rate, which is necessary to determine the number of cells that transition between classes at each annual time step, in this case for forest to deforestation. The transition rate was calculated using a sub-model in DINAMICA-EGO called “Determine Transition Matrix,” which uses maps of the initial state (cumulative deforestation by 2007) and final state (cumulative deforestation by 2013). This tool generates two matrices: the annual transition matrix (Multiple Step) and a global transition matrix (Single Step). “Multiple Step” portrays the process of change between the classes that occurs each year, while “Single Step” portrays the change over the whole analysis period (Leite-Filho et al., 2020). The simulation used the annual transition matrix (Multiple Step) , which reflects the average annual transition in the calibration period (2007 to 2013).

However, simply applying the deforestation rate provided in the annual transition matrix would result in a constant rate across all model interactions. Thus, considering that deforestation rates actually fluctuate over time (increasing and decreasing), whether as a result of financial crises, conflicts, climatic events, political decisions and other factors, this study included an increasing and reducing factor for deforestation rates, which was applied for interval periods of six years (period equal to the reference period used to calibrate the model).

To represent increase in deforestation, an index was added to the transition rate (Multiple Step) that considered the deforested area in the previous year plus the average percentage increase in all years in which deforestation increased in the period from 2000 to 2014 in the state of Amazonas. This represented the increase in deforestation in the study area by means of the following equation:

$$Ind.t = ((AD2-AD1)\ 100)/AD1) + Md_i \qquad \text{(Eq. 1)}$$

Ind.t = Transition Index
AD1 = Area deforested in Year 1 (km^2)
AD2 = Area deforested in Year 2 (km^2)
Md_i = Average annual deforestation during the years in which there was an increase (period from 2000 to 2014)

To represent reduction in deforestation, Equation 2 follows the same principle as Equation 1, using the average percentage decrease in all years in which there was a reduction in deforestation during the period from 2000 to 2014.

$$Ind.t = ((AD2-AD1)\ 100)/AD1) - Md_d \qquad \text{(Eq. 2)}$$

Ind.t = Transition Index
AD1 = Area deforested in Year 1 (km^2)
AD2 = Area deforested in Year 2 (km^2)
Md_d = Average annual deforestation during the years in which there was a reduction (period from 2000 to 2014)

The increase and decrease factors (Md_i and Md_d) were calculated based on the average increase and decrease in deforestation during the period from 2001 to 2014, to better represent the trends of increase and decrease over time, which were defined as follows: 0.26 for increase and 0.20 for reduction. The years in which there were increases and decreases in deforestation in the state of Amazonas are shown in the Supplementary Material (Appendix 5, Fig. S4), as well as an example of the fluctuation of deforestation rates over time (Fig. S6). The present method allowed the transition rates to fluctuate with each iteration of the model, which means that as there is a change in the landscape at each time step, the (annual) transition rate is updated at each iteration in relation to the available forest area in each region. A summary and the input data is shown in Appendix 5 and Table S4 of the Supplementary Material.

The spatial allocation functions for the new deforestation patches used in the model were Patcher and Expander, where the Patcher function creates new areas (patches) of transition separate from the already deforested areas, while the Expander function is responsible for enlarging already-deforested areas (Leite-Filho et al., 2020). In this study, several rounds of parameter adjustments were carried out and, in the validation test, the best result was found to be achieved was using 30% as a value for the Expander function and 70% for the Patcher function. As for the size of the deforestation patches, the average range of the size of the deforestation polygons of each region defined in the study was calculated during the calibration period. The settings used to allocate deforestation patches through the Patcher and Expander functions, including the percentages adopted, are available in the Supplementary Material (Appendix 6, Table S6).

Considering that the model deals with the impact of roads on landscape change, the road builder module was coupled to the model, using the map of official and endogenous roads as input. This module calculates the relative cost that a road has in crossing a cell in the land-use map, depending on the destination given to the cell (protected lands, non-destined forest areas, settlements, etc.). For this, we used an attractiveness map (which indicates the most favorable areas for road construction) and a friction map (which indicates the areas with greater restrictions for road construction) (Leite-Filho et al., 2020). The settings used in the road-builder module can be seen in the Supplementary Material (Appendix 7, Table S7).

2.3.3. Model validation

After calibration (2007 to 2013), a simulation model was used for the period from 2014 to 2021 in order to calculate the change that occurred in this interval and validate the resulting map of the simulated model for 2021 by comparison with the real map from PRODES 2021. For validation this study simulated a period that was different from the calibration period in order to assess how good the model is at predicting changes in the landscape, based on the procedures used in past studies (Siqueira-Gay et al., 2022).

The validation method applied in this study was the fuzzy similarity method (Hagen, 2003), adapted by Leite-Filho et al. (2020). This method employs a constant decay function that measures the spatial adequacy between two maps through multiple-window similarity analysis, that is, if the same number of change cells is found in the window, the fit will be 1, regardless of their locations, and zero if the same number of change cells is not found (Leite-Filho et al., 2020). Simply put, the model makes the comparison through window sizes, that is, with the number of cells corresponding to the resolution used in the modeling. For example: in this study the resolution adopted was 100 m, so window 1 (1 × 1) corresponds to 100 m × 100 m (0.01 km^2), window 3 (3 × 3) = 300 m × 300 m (0.09 km^2), and so on.

Because the comparison is made using both maps (simulated and observed), the results can generate rates with minimum and maximum similarity values, which can vary from 0% to 100% (0% indicates that the maps are completely different and 100% indicates they are identical). In this study we adopted the minimum similarity value as a reference. We compared the simulation results with a null model, which uses the same maps and input rates but with weights-of-evidence values set to zero. The null map was also compared with the observed map (PRODES 2021). To be considered efficient, the proposed model must win in all comparisons made with the null model. Further details can be found in the supplementary material (Appendix 8).

2.3.4. Projection of future scenarios

The current approach considers the trends in the expansion of territorial occupation by different local groups based on the dynamics of historical deforestation for the Amazon (Business as Usual, or BAU), which reflects occupation dynamics and conflicts that influence landscape change along highways (Castro et al., 2004; Brito & Castro, 2018; Fearnside, 2022a). Thus, deforestation rates were not projected based on the perspective of improving the environmental management in the area, such as strengthening and increasing the autonomy of public command-and-control institutions, public policies aimed at sustainability or achieving the goal of reducing emissions stipulated in international agreements, as this depends on the long-term commitment of state and federal governments.

Two environmental prognosis scenarios were developed for the period from 2021 to 2100: a) Scenario 1 (BAU_1) - Highway BR-319 without paving (the current status with seasonal maintenance and with degradation in the rainy season, with the pending reconstruction and paving project not approved); b) Scenario 2 (BAU_2) – Highway BR-319 with paving (the reconstruction and paving project is assumed to be authorized and started in 2025).

For the BAU_1 scenario, the averages of the historical transition rates from the calibration period (2007 to 2013) obtained from each region of the study area were applied according to the methodology presented in the item 'model validation', from 2021 to 2100. For the BAU_2 scenario, the transition rates followed the same principles as the BAU_1 scenario until the beginning of the paving of Highway BR-319 in 2025, when an increase in the deforestation rate begins as a result of the migratory flow resulting from the road improvement and the expansion of the planned road network until 2100. Post-paving rates were obtained from other regions within the study area itself, as defined below.

For the Scenario BAU_2, which considers Highway BR-319 to be paved from 2025 onwards, the rates found in Regions 3 and 4 (where the sections of the BR-319 are located) take on present the same rates found in Region 1 (area with a higher deforestation rate) Regions 3 and 4 would be new frontiers for expansion of ranching if BR-319 is paved, and in Region 5 (Manaus), which will have the rate of Region 3, a region close to the capital of Rondônia (so that Region 5 has a rate similar to that near a state capital in the 'arc of deforestation').

After 2028, the transition rate found in Region 7 (providing Highway AM-366 is built as a result of the BR-319 highway), started to have the same rate as in Region 1 (same principle adopted to represent the Regions 3 and 4, if AM-366 is built). The Region 1 rate was chosen because it represents a continuation of the expansion of deforestation towards the western part of the study area due to the influence of migration to Amazonas from the states of Pará, Rondônia, and Mato Grosso. We therefore chose Region 1 as a reference to represent the amount of deforestation.

Regardless of the applied rate, the model allows the use of weights-of-evidence coefficients from other regions that can better simulate what is intended to be represented. Thus, the weights-of-evidence coefficients were also replaced to better represent the influence of paved roads in the model, so Regions 3 and 4 (site of the BR-319 highway), and Region 5 (region with road connecting to BR-319, and therefore becoming a new agricultural frontier), started to have the same weights-of-evidence coefficient as in Region 6 (which is a region with the paved Highway BR-364 in the 'arc of deforestation').

Considering the construction plan for Highway AM-366 (without paving), Region 7 now has the same weight of evidence as Region 1 (which is a region with the unpaved Highway BR-230 in the 'arc of deforestation' in the state of Amazonas). In addition, to complement the analysis of the impact of deforestation, a paving plan was made for Highway AM-366 for the year 2050, after which it started to change the weights-of-evidence coefficients to be more similar to those of Region 6 (i.e., to resemble region with a paved highway: part of the Porto Velho–Rio Branco stretch of BR-364).

The paving plan for Highway AM-366 is justified by the fact that the proposed road is located in a region planned for oil and gas extraction, which may favor financing or raising funds for construction, in addition to a greater possibility of political interference with the licensing body. However, it is worth noting that, considering the applied transition rates, the result of the amount of deforestation does not change.

Patcher and Expander allocation followed the same principles as for the parameters used in road construction.

The plan for the construction and paving of the planned highways followed the principles of area availability and occupation opportunity because, regardless of government plans for building a highway, when there is an available area and opportunity, the illegal occupants of the area begin to follow the planned route of a highway, opening unofficial roads and branches on the proposed official highway. This fact can be observed in an area in Region 4, where an illegal road or “branch” is already being built on the route of the proposed Highway AM-366 (Fearnside, 2022b). Thus, for the present study, a three-year construction schedule (whether official or not) was adopted to start after the paving of BR-319 (Table 1).

Table 1 The schedule for the construction and paving of the planned highways influenced by the implementation of BR-319.

Road	Segment	Start
BR-319	Manaus– Porto Velho	2025*
AM-366 (Segment 1)	Tapauá – AM-343	2028
AM-343	Coari - AM-366	2028
AM-366 (Segment 2)	Entroncamento AM-366 - Tefé	2031
AM-366 (Segment 3)	Tefé - Jutaí	2034
AM-356	BR-319 - Borba	2028
AM-360	BR-319 – Novo Aripuanã	2028
AM-366 (all segments) and AM-343	Tapauá – Coari - Jutaí	2050*

***** Pavement estimate.

The application of transition rates in both scenarios followed the same methodology applied for the validation phase. However, the values for the 'average of years in which there was an increase and decrease in deforestation' (Md_i and Md_d) were adjusted in both scenarios to better represent the trends, using the average increase and decrease over the period from 2000 to 2021. The value of 0.32 was adopted as an increase factor and 0.19 as a decrease factor, with intervals of 6 years starting in 2021(Table S5, Supplementary Material).

3. RESULTS

3.1. Validation

The validation compared the 2021 simulated deforestation map with the 2021 deforestation obtained by the PRODES mapping in 2021, which is considered as a reference for observed deforestation. This method considers the values of the similarity index of 50% sufficient for model validation (Soares-Filho et al., 2013). The value of the minimum similarity index obtained was 51% for the simulation model in a window of 11 × 11 cells.

In addition to the validation for 2021, the results were compared to a null model. In the null model the same input maps and transition rates were used, but with the weights-of-evidence coefficients set to zero, producing the result shown in Fig. 5.

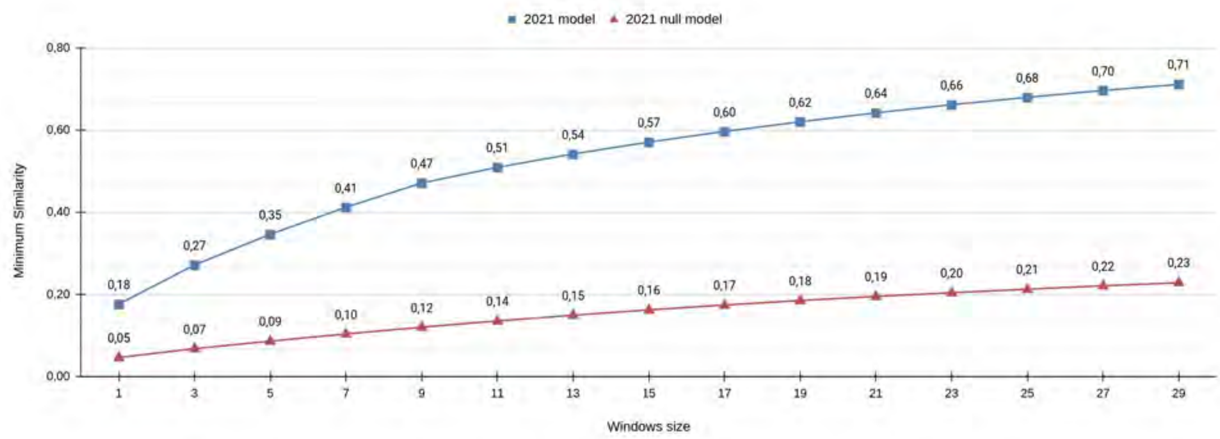


Fig. 5 Validation results for 2021 with minimum similarity and with the null model, using the constant decay method.

Regarding the comparison of the simulated deforestation, the validation showed a difference of -0.54% in relation to the reference deforestation for the year 2021, resulting in a difference of -313.92 km^2 (Supplementary Material, Appendix 8, Table S8). The results for each region are shown in the Supplementary Material (Fig. S8, Appendix 8).

3.2. Deforestation prediction for the years 2050 and 2100

In this section, the results of the scenarios will be presented, highlighting the simulated changes by 2050 and by 2100. The results show that, for deforestation in BAU_1, there is an increase of 200.24% up to 2050 and 607.42% up to 2100, in relation to that observed in the PRODES 2021 map. For BAU_2, there is an increase of 224.12% by 2050 and 711.33% up to 2100, for the entire modeled area, as shown in Fig. 6.

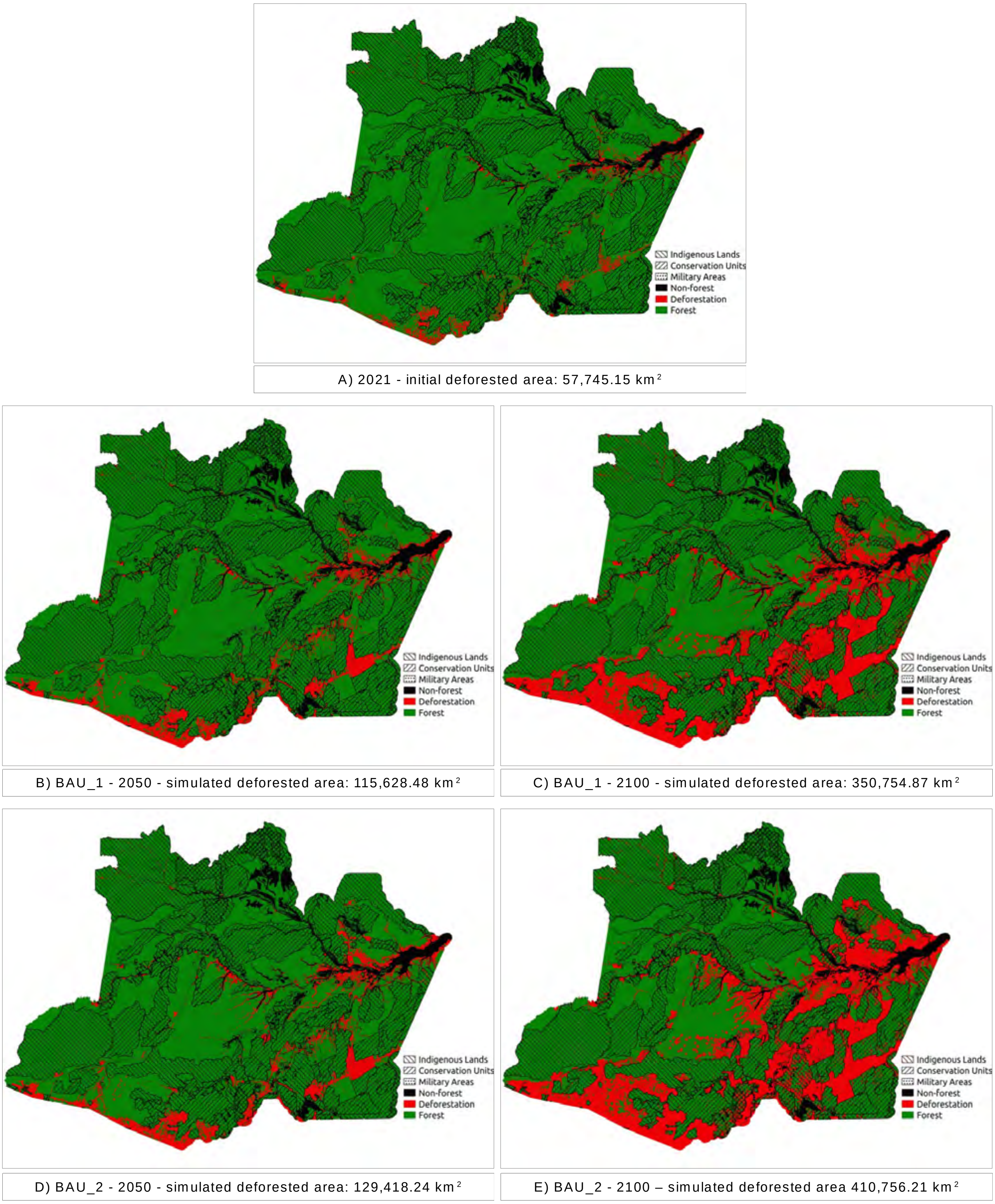
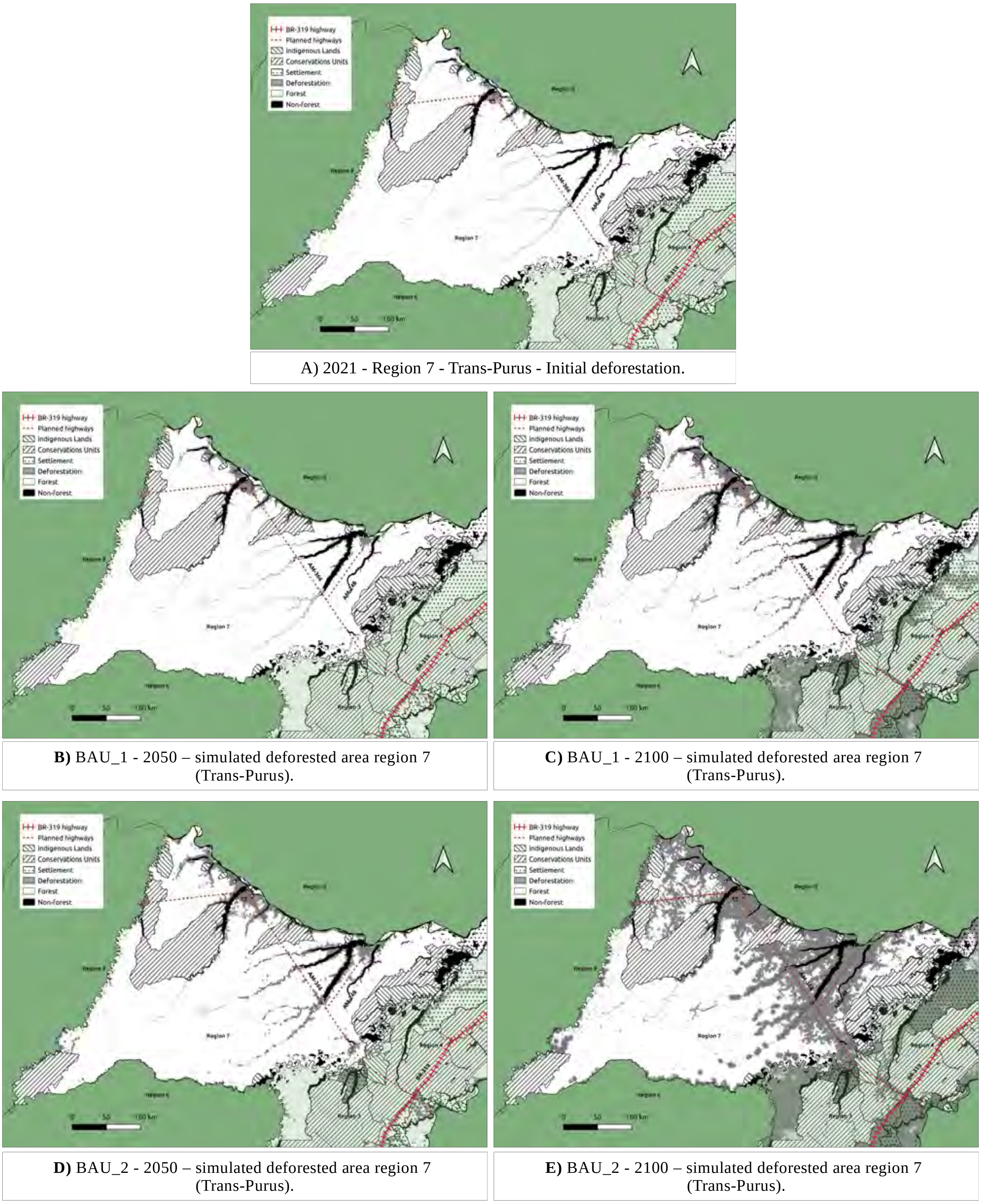


Fig. 6 Evolution of cumulative deforestation for the period from 2021 (A) to 2050 and 2100 in the BAU_1 (B and C) and BAU_2 (D and E) scenarios. In this study, "non-forest" refers to those areas not considered by PRODES/INPE in the calculation of deforestation in the Amazon (savannas, water, rocky outcrops, etc. - http://terrabrasilis.dpi.inpe.br/).

For the BAU_1 *s*cenario in the Madeira-Purus interfluve (Regions 3 and 4) where the BR-319 Highway is located, there were increases of 197.37% up to 2050 and 600.95% up to 2100 in Region 3 and increases of 241.08% up to 2050 and 762.04% up to 2100 in Regions 4. Especially for the northern stretch of Highway BR-319 (Region 4, which has more area available for deforestation) after paving (BAU_2) there were increases of 260.08% up to 2050 and 843.65% up to 2100.

Another part of Amazonas that draws attention is the Trans-Purus region in the center of the state (Region 7). This is due to the possible construction of Highway AM-366, which would connect to BR-319 (BAU_2). The BAU_2 scenario shows an increase of 359.48% by 2050 and 1458.91% by 2100 (Fig. 7, panels D & E).



A) 2021 - Region 7 - Trans-Purus - Initial deforestation.

B) BAU_1 - 2050 – simulated deforested area region 7 (Trans-Purus).

C) BAU_1 - 2100 – simulated deforested area region 7 (Trans-Purus).

D) BAU_2 - 2050 – simulated deforested area region 7 (Trans-Purus).

E) BAU_2 - 2100 – simulated deforested area region 7 (Trans-Purus).

Fig. 7 Evolution of cumulative deforestation for the period from 2021 (A) to 2050 and 2100, in scenarios BAU_1 (B and C) and BAU_2 (D and E) in Region 7 (Trans-Purus) as a result of the construction of Highways AM-366 and AM-343.

Region 5 (BR-174 from Manaus to the border with the state of Roraima) would have an increase of 225.36% by 2050 and 734.81% by 2100 due to the influence of the reconstruction of BR-319 (BAU_2). Thus, for the regions influenced by Highway BR-319 (Regions 3, 4, 5 and 7) deforestation would have an increase of approximately 60% in BAU_2 (159,961.31 km^2) in relation to BAU_1 (99,959.97 km^2). The results for all regions are shown in Table 2.

Table 2 Increase in cumulative deforestation by region and percentage of increase in cumulative deforestation over the simulated period in relation to 2021.

Region	PRODES 2021	BAU_1 2050 (km^2)	%	BAU_2 2050 (km^2)	%	BAU_1 2100 (km^2)	%	BAU_2 2100 (km^2)	%
1	9,042.42	27,569.06	304.89	27,569.06	304.89	92,897.55	1,027.35	92,897.55	1,027.35
2	5,369.36	7,272.21	135.44	7,272.21	135.44	17,114.99	318.75	17,114.99	318.75
3	4,469.53	9,918.68	221.92	11,624.33	260.08	31,599.30	706.99	37,707.12	843.65
4	4,713.67	8,205.97	174.09	10,514.33	223.06	23,586.79	500.39	32,272.10	684.65
5	7,634.83	12,083.39	158.27	17,205.73	225.36	33,927.84	444.38	56,101.63	734.81
6	19,040.05	38,864.17	204.12	38,864.17	204.12	117,380.29	616.49	117,380.29	616.49
7	2,322.31	3,694.81	159.10	8,348.22	359.48	10,846.04	467.04	33,880.46	1458.91
8	3,327.30	5,046.21	151.66	5,046.21	151.66	14,387.02	432.39	14,387.02	432.39
9	1,825.68	2,973.98	162.90	2,973.98	162.90	9,015.05	493.79	9,015.05	493.79
Total	57,745.15	115,628.48	200.24	129,418.24	224.12	350,754.87	607.42	410,756.21	711.33

Roads played an important role in the distribution and dispersion of deforestation over time in the proposed model. Fig. 8 cuts out the study area to show how deforestation evolves around the simulated roads for the years 2050, 2060, 2070, 2080, 2090 and 2100. According to the model, a cluster of deforestation ends up attracting other deforestation, which can occur on the banks of rivers without the presence of roads. However, a large part of the deforestation is conducted along unofficial roads that branch off from the official roads (in Brazil, the pattern of these side roads is called the "fishbone"). This pattern develops along roads connecting to riverside towns and cities, as can be seen in the evolution of deforestation shown in Fig. 8, corroborating the studies by Castro et al. (2004), Nepstad et al. (2006), Barber et al. (2014), dos Santos-Júnior, et al. (2018) and Fearnside (2022a,b).

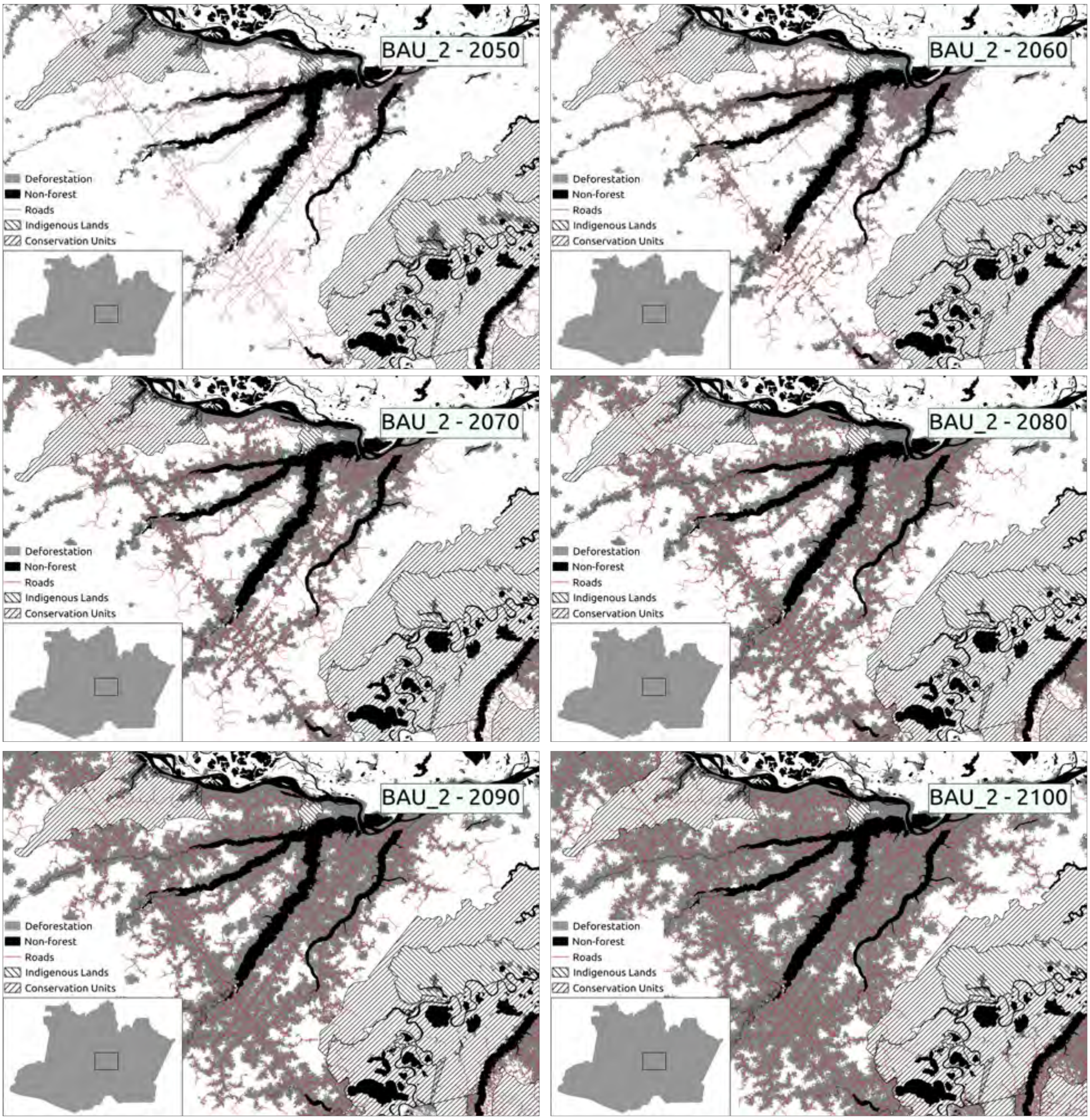


Fig. 8 Evolution of deforestation around the simulated roads over time in the BAU_2 scenario. The figure shows part of the region of influence of AM-366 (Trans-Purus).

We can see that deforestation has increased in all protection categories (except for military areas, which have very low deforestation). When comparing the deforestation of protected areas in relation to the total forest loss (inside and outside protected areas) after 2021, an increase of deforestation in conservation units by 2,153.60 km^2 up to 2050 can be observed in the BAU_1 scenario, and 28,656.73 km^2 up to 2100, corresponding to 3.72% and 9.78%, respectively, in relation to total deforestation. In the BAU_2 scenario, deforestation in the protected areas was 1,960.65 km^2 in 2050 and 34,612.13 km^2 in 2100, corresponding to 2.73% and 9.80%, respectively, of the total deforested area.

In indigenous lands, projected deforestation after 2021 was 1,042.81 km^2 in 2050 and 19,911.23 km^2 in 2100 for the BAU_1 scenario, corresponding to 1.80% and 6.79%, respectively, in relation to total deforestation. For the BAU_2 scenario, the total area of deforestation in indigenous lands was 964.44 km^2 in 2050 and 21,079.15 km^2 by 2100, respectively, from which 1.34% and 5.97% of the total deforested area were after 2021. Regarding the total area of protected areas, deforestation reaches 0.52% by 2050 and 7.91% by 2100, in the BAU_1 scenario and 0.48% by 2050 and 9.08% of the total area of conservation units and indigenous lands up to 2100 in the BAU_2 scenario. Fig. 9 presents the relationship between deforestation in protected and non-protected areas, showing the importance of protected areas for the conservation of forests in the Amazon.

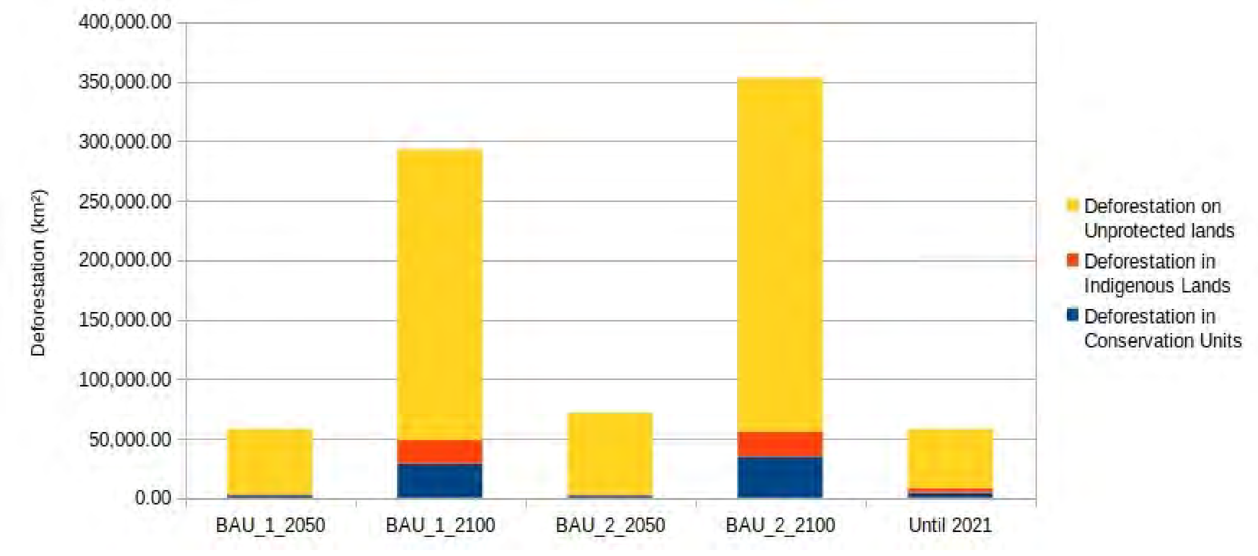


Fig. 9 Deforestation in protected areas (conservation units and indigenous lands) and non-protected areas (settlement projects are not considered to be protected areas).

For settlement projects, according to the results of the projection for the BAU_1 scenario, the deforestation that occurred after 2021 was 16,897.26 km^2 by 2050 and 48,407.66 km^2 by 2100, corresponding to 41.22% and 19.79% in relation to the deforestation outside protected areas. For the BAU_2 scenario, deforestation after 2021 was 21,660.76 km^2 by 2050 and 57,334.82 km^2, which corresponds to 43.31% and 19.39% in relation to total deforestation (excluding protected areas), respectively (Fig. 10). Regarding the total area of settlements, deforestation reaches 22.76% up to 2050 of the total area of settlements and 65.19% up to 2100 in the BAU_1 scenario, and it reaches 29.17% up to 2050, and 77.21% up to 2100 in the BAU_2 scenario.

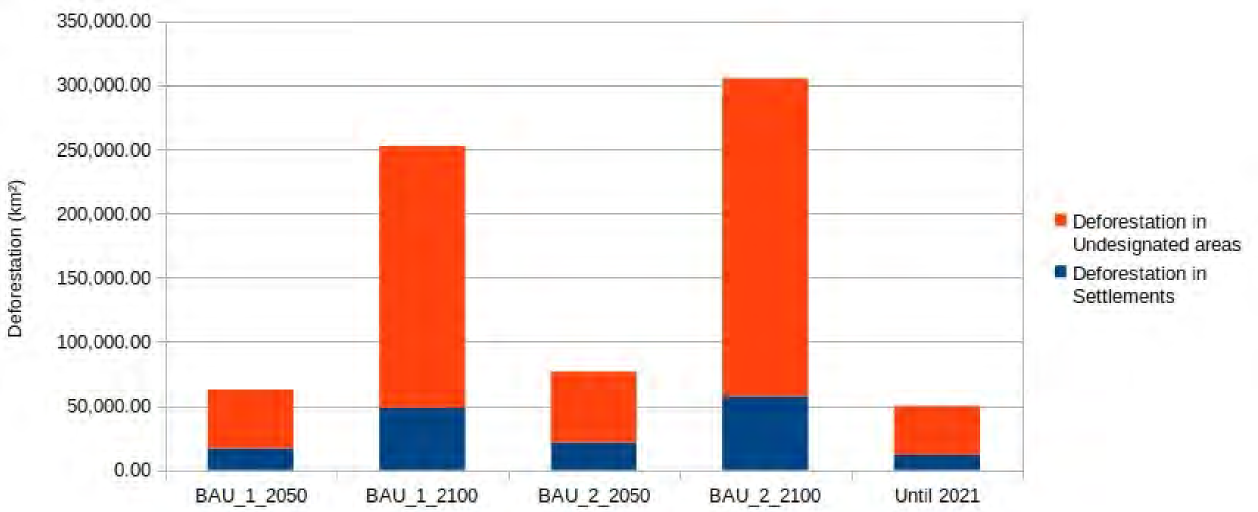


Fig. 10 Deforestation in settlement projects and non-designated public land.

4. DISCUSSION

4.1 Simulated Deforestation

Although the method considers similarity index values above 50% to be enough to validate the model, which means that the amount of change correctly predicted is greater than the sum of the various types of error (Pontius-Jr et al., 2007; Soares- Filho et al., 2013), there is no general rule for calibration and validation in the land-use modeling process (Rykiel, 1996; Mazzotti &Vinci, 2007). However, it is understood that the model must satisfactorily represent the spatial dynamics of deforestation in the study area.

In the current study, the model reached 51% in the 11 × 11 window, which corresponds to the similarity in an area of 1.21 km^2. Some studies carried out in smaller areas in Amazonia also found similarity starting at 50% in the 11 × 11 window or smaller, such as Yanai et al. (2012) in the 5×5 window, Maeda et al. (2011) in the 11 × 11 window, Barni et al. (2015) in the 7 × 7 window, Roriz et al. (2017) in the 5 × 5 window, Ramos et al. (2018) in the 11 × 11 window; dos Santos-Júnior et al. (2020) reached 49% in the 11 × 11 window, and Santos et al. (2021) reached 57% in the 7 × 7 window.

In addition, the accuracy was checked by comparison with a null model that, for the same window, reached 14% similarity. According to Pontius-Jr et al. (2004), a model becomes more accurate than the null model when the spatial resolution is increased, that is, the quality of the resolution scale influences the result of a predictive model when compared to the null model. Considering the extent of the study area and the spatial resolution used, the validation results achieved in this study can be considered satisfactory.

In the model scenarios (BAU_1 and BAU_2) we sought to represent the current trend to increased deforestation rates in the Amazon. After the large reduction in annual deforestation from 2004 to 2012, a gradual and consistent increase in rates was observed beginning in 2012, when the Brazilian Forest Code was altered due to the strong political representation of agribusiness in the National Congress (Fearnside, 2022a). Many environmental regulations were also being revoked, especially during the 2019-2022 presidential administration of Jair Bolsonaro.

The results show that in both scenarios (BAU_1 and BAU_2) there is an evident increase in deforestation in the southern part of the Amazon, influenced by roads, settlements, and the ‘arc of deforestation.’ Following this trend, the results show increases in deforestation in all of the modeled area along Highway BR-319, as well as along connecting highways such as AM-366, especially for the BAU_2 scenario due to the approval of the reconstruction and paving of Highway BR-319. This corroborates the predictions of Fearnside et al. (2009) and dos Santos-Júnior et al. (2018), in addition to models that considered projected road building in the Amazon region (Laurance et al., 2001; Soares Filho et al., 2004, 2006; Aguiar, 2006, 2016).

Deforestation of protected areas and Indigenous Lands can also increase considerably, according to various studies carried out in the region (Ferrante & Fearnside, 2019; Ferrante et al., 2021a,b). However, these areas continue to confer a certain resistance to environmental degradation by deforestation, as demonstrated by the current deforestation data available in the PRODES images from the National Institute for Space Research (INPE), as well as in the reports of the programs of Ministry of Environment (MMA) to combat and control deforestation from the (MMA, 2016, 2018). Therefore, it is important to create, implement, maintain, monitor, and inspect protected areas in the Amazon.

Regarding settlement projects, the study shows that there is a significant increase in all categories, indicating that creating “sustainable-use settlements” in the region does not provide the desired protection (Yanai et al., 2017). Settlements currently represent 15.66% of the deforestation in the study area, but for deforestation up to 2100 this percentage rises to 65.19% in the BAU-1 scenario and 77.22% in the BAU_2 scenario. This corroborates the studies by Yanai et al. (2017), who indicated that settlements play an important role in the dynamics of deforestation and future carbon emissions in the Brazilian Legal Amazon region.

Simply giving the news of a settlement approval starts a race in search of legalized lands made available by the government, according to the dynamics explained by Castro et al. (2004). This is exemplified by the Realidade Sustainable Development Project (PDS) that was created in 2007 around the BR-319 in the municipality of Humaitá (INCRA, 2015). The mere announcement of the approval of this PDS set off a race in search of land, promoting invasion of the land and dividing it into small lots for sale to new arrivals, with no interference from the responsible government agency (The National Institute for Colonization and Agrarian Reform, or INCRA). Thus, making logging, agriculture, extensive livestock, speculation, and land grabbing grow in the settlement's surroundings and along the highway, as observed by Fearnside (2018), Andrade et al. (2021), and Ferrante et al. (2020, 2021) in studies carried out in the region, demonstrating that the pattern of deforestation dynamics continues until the present day.

Another important issue is the proposed construction of State Highway AM-366, which would connect the BR-319 highway to the western part of the state of Amazonas (in this study represented by Region 7, see Fig. 5), one of the most preserved areas in Amazonia, and essential for the environmental services that the forest offers (Fearnside, 2020; Fearnside et al., 2020). An important source of impact would also be the advance of the 'arc of deforestation' towards the north (Region 5) along the Federal Highway BR-174, which connects Manaus to Boa Vista and the border with Venezuela (Fearnside & Graça, 2009; Barni et al., 2015).

Although the roads are considered strategic and important because they reduce the isolation of the population and facilitate access, tourism and the flow of products, the development model based on the expansion of road axes in the Amazon region is the main promoter of environmental degradation through its role in facilitating both the migration of population to the region and the expulsion of population to more distant frontiers as smallholdings are bought up by large cattle ranchers. The forest is lost in this process, with major environmental impacts. We can say that Brazil has still not managed to find an action strategy that is efficient to reconcile the interests of the population that wants more highways, with the preservation of the environment. The BR-163 (Santarém-Cuiabá) Highway serves as an example: deforestation increased tremendously after the highway was reconstructed and paved, despite all attempts to develop policies, plans and programs to reduce this environmental damage (Castro et al., 2004; Araújo et al., 2008; Brito & Castro, 2018).

As observed in the maps generated by the model, the impact of deforestation goes beyond the official 40-km influence area defined by Interministerial Ordinance 60, of 24 March 2015 for the environmental licensing processes of highways in the Amazon region. This demonstrates that the environmental licensing process would benefit from modeling the impact before defining the radius of influence in decision making. Fig. 11 shows the deforestation around Highway BR-319 and the buffer area of 40 km (for the stretch where the Installation License for reconstruction of the highway is being requested), and we can observe the continuous deforestation beyond the limits of the 40-km buffer.

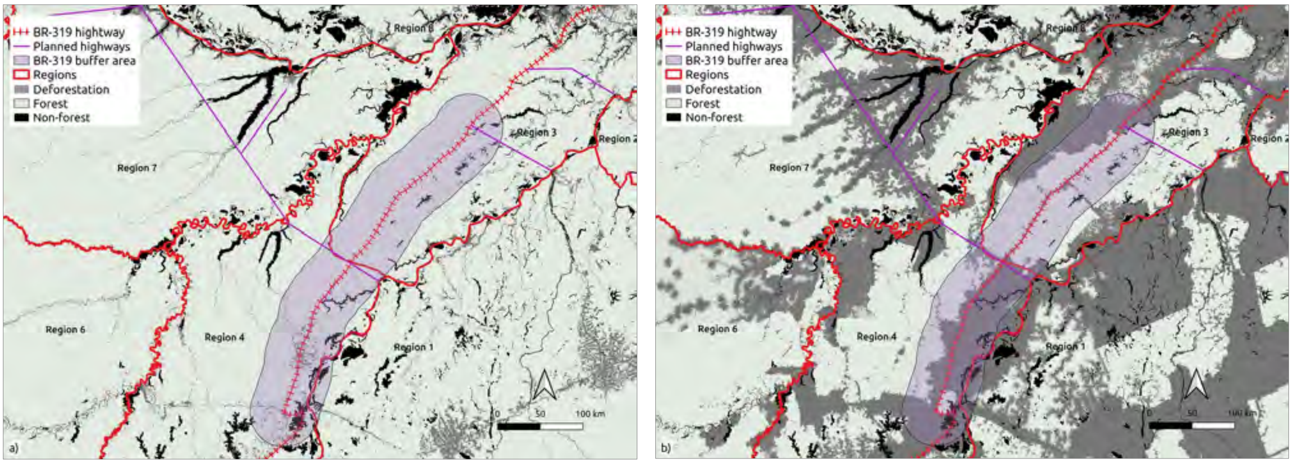


Fig. 11 Official 40-km area of influence defined by Interministerial Ordinance 60 of 24 March 2015) for environmental licensing of highways in the Amazon region (a & b); the expansion of deforestation in the BAU_2 scenario is shown for 2100 (b) in relation to the reference year (a).

Thus, a more comprehensive modeling study similar to the current one could be used to define the probable area of a road project's impact in the Amazon. This gives the environmental impact study more tools for decision making, which makes it possible to define the best mitigation measures to reduce negative impacts and to have a more realistic assessment of impacts for decisions on whether these highways should be built. While decisions on road building should consider all possible impacts, it is understood that environmental licensing is limited in its ability to require that the entrepreneur repair or mitigate the possible indirect impacts of an enterprise, such as the construction of connecting highways by the local authorities or negative influence on other states.

It is therefore urgent for Brazil to adopt tools such as the strategic environmental assessment (*Avaliação Ambiental Estratégica* = AAE), which is a planning and support instrument for strategic decision-making on the socio-environmental impacts of the Brazilian government's Policies, Plans and Programs (PPP) initiative (Partidário, 2001, 2003; Pellin et al., 2011), such as Avança Brasil 2000 and the 2004-2007 Pluriannual Plan, which included the reconstruction of highways in the Amazon (Fearnside & Graça, 2009). Because, as we commonly see in the Amazon, a simple PPP announcement for the installation of any large enterprise is capable of promoting migration and irregular occupation of land by people in search of opportunities and cheap land, consequently leading to environmental degradation such as what is occurring around BR-319.

5. CONCLUSION

The results presented in this study reflect the contribution of roads to advancing the agricultural frontier in Brazil's state of Amazonas, despite the limitations of environmental models in representing the complexity of the dynamics of deforestation in the Amazon. Given the assumptions of our model, we conclude that by 2100 reconstruction of Highway

BR-319 (BAU_2) would increase deforestation along the highway (Regions 3 and 4) and in the regions with roads directly connected to BR-319 (Regions 5 and 7) by 60% in relation to deforestation in the projected scenario without reconstruction (BAU_1).

In relation to protected areas (indigenous lands and conservation units), despite deforestation increasing over time, these areas continue to play an important role in protecting the forest, and it is up to the government to increase protection, monitoring, and inspection, as well as to create new areas, in view of the advance of deforestation in non-designated public forests. Unlike protected areas, settlements do not provide environmental protection, regardless of their modality, and it is the government's responsibility to create environmental control mechanisms.

The results show that modeling the deforestation of a road enterprise can be part of the processes of environmental licensing and strategic environmental assessment for the formulation and implementation of policies, plans, and government investment programs in the Amazon region. Models of this type can better define the area of influence and expansion of socio-environmental impacts, as well as provide information for measures to mitigate and control negative impacts and to guide decision-making on whether or not to implement construction projects.

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Declarations

Competitive Interests

We declare that the authors have no conflicting interests as defined by Springer, or other interests that could influence the results and/or discussions reported in this article.

Availability of data and material

Datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Third party material

All material is the property of the authors and no permissions are required.

Double Publication

The results/data/figures in this manuscript have not been published elsewhere, nor are they under consideration by another publisher.

Ethical responsibilities

All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

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SUPPLEMENTARY MATERIAL

Reconstruction of Highway BR-319: Deforestation simulation in Brazil's state of Amazonas

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APPENDIX 1.

Law No. 12,651, of 25 May 2012 established general rules for the protection of vegetation, permanent preservation areas (APPs) and legal reserve areas, forest exploitation, the supply of forest raw materials, control of the origin of forest products and the control and prevention of forest fires; the law also foresees economic and financial instruments to achieve its objectives. This law repealed and replaced Law No. 4771, of 15 September 1965 (the former Forest Code).

APPENDIX 2.

The DINAMICA EGO software was developed by the Center for Remote Sensing of the Federal University of Minas Gerais (UFMG) to support multivariate and non-linear environmental modeling. It is based on cellular automata, consisting of an array of n dimensions of cells according to their previous condition and the spatial arrangement of neighboring cells through a set of transition rules, where each cell represents the possibility of converting from one state to another in a given scenario (Soares-Filho *et al*., 2002, 2004, 2006; Lima, 2013; Oliveira *et al*., 2019). The DINAMICA-EGO modeling environment (Fig. S1) involves a series of operators called "functors" that can be understood as a process that acts on a set of input data on which a finite number of operations is applied, producing as output a new dataset (Rodrigues, 2007; Lima, 2013).

Models must be built to answer: WHERE changes in land cover will occur; HOW MANY changes will occur each year; and HOW the areas will be spatially distributed (Vitel, 2009).

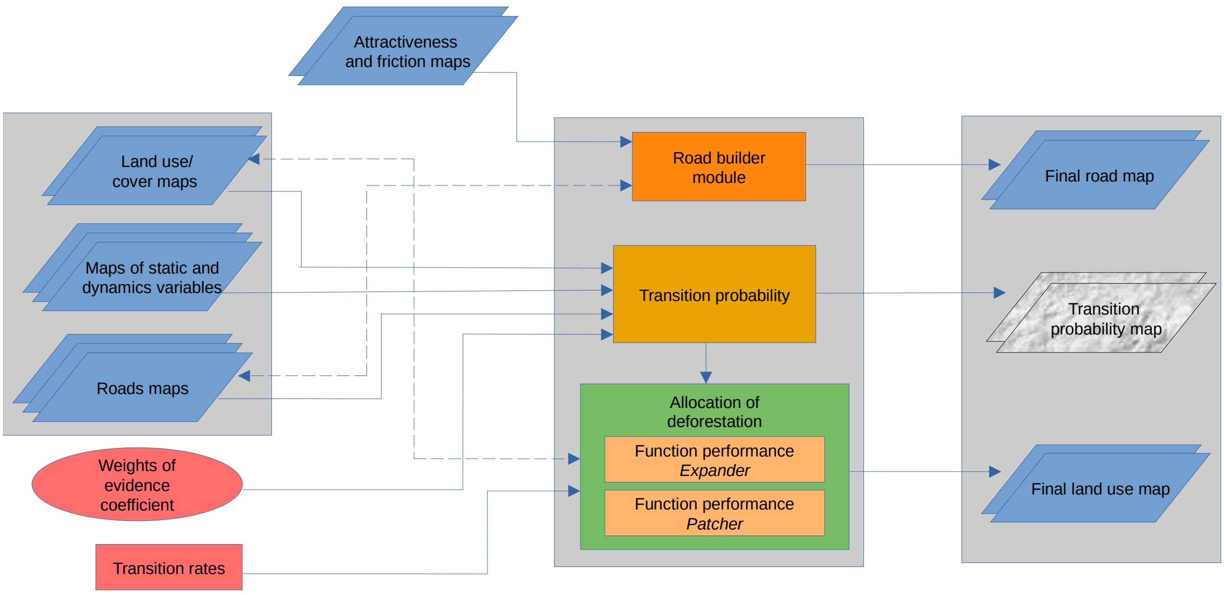


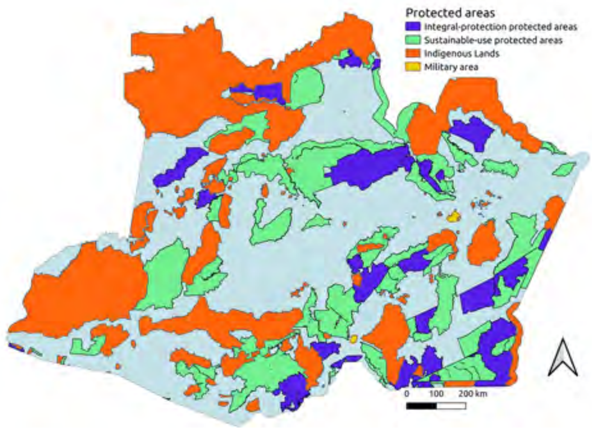
Fig. S1 Conceptual diagram of the deforestation simulation model. Dashed line is where the looping occurs adding the new deforestation and roads built in each time step (year), entering the transition probability calculations, allocating new deforestation patches.

APPENDIX 3.

Table S1 Parameters used as input data for DINAMICA-EGO.

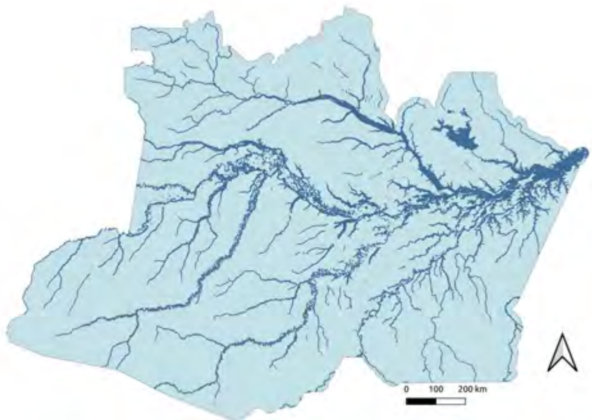
	Variables	Source
	Land cover: deforested area, forest, and non-forest (savannas, water, rocky outcrops, etc.)	PRODES for 2007 and 2013 (INPE, 2020)
Static Variables	Protected Areas (integral-protection PAs; sustainable-use PAs; indigenous lands; and military areas)	ICMBIO (2019), SEMA (2020), FUNAI (n.d), AMN (2021)
	Settlement project (Agro-extractive Settlement Project, or PAE; Sustainable Development Settlement Project, or PDS; Rapid Settlement Project, or PAR; Forest Settlement Project, or PAF; Directed Settlement Project, or PAD; and [traditional] Settlement Project, or PA)	INCRA (n.d)
	Oil and gas prospecting/research area	Manual vectorization
	Hydrography (watercourses)	INPE (2020)
Dynamic variables	Highways and Roads (official and endogenous)	DNIT (2013), plus manual vectorization of endogenous roads for the year 2013.
	Deforestation	PRODES for 2007 and 2013 (INPE, 2020)

In the state of Amazonas there are areas of vegetation that were suppressed for research and for prospecting for oil and natural gas, which, in the land-cover map provided by INPE, appear as cumulative deforestation. Therefore, in the model these areas can attract excessive allocation of deforestation around them and do not represent the dynamics of deforestation in the Amazon region as a whole, which is dominated by the expansion of livestock, agriculture, and mining in the vicinity of roads and previous deforestation. Therefore, a map, with a buffer of 1500 m of each oil and gas prospecting and exploitation area was prepared to serve as a “correction factor,” and these areas were given a weight of evidence equivalent to a sustainable-use protected area, which creates friction against the advance of deforestation in these areas but does not prevent deforestation if a planned road passes through the area. This allows the model to allocate new deforestation in places that are more susceptible to land-use change.



a) Protected areas

b) Settlement projects



c) Hydrography (watercourses)

Fig. S2 Maps of static variables.

APPENDIX 4.

Regionalization of the study area makes it possible to individualize each region, thus identifying specific parameters such as transition rate and weights-of-evidence coefficients in the calibration, allowing the simulation result to better represent reality. In addition, it can suggest how a particular region will behave if the variables in play are different from those in other regions. This was the case when we used transition matrices and the weights-of-evidence coefficients from another region to simulate a change based on what we wanted to represent (e.g., using weights-of-evidence coefficients from Region 6 used in Regions 3, 4 and 7 after the reconstruction and paving of BR-319).

The regions used in this study are not official. They were defined by the authors, taking into account regional characteristics such as the proximity and influence of the state capitals (Manaus and Porto Velho), hydrographic limits, livestock expansion areas, protected areas, non-protected areas, fishing activity, wood industry, possibility of expansion of the arc of deforestation, and the influence of paved roads and of regions that presented different deforestation rates. This was needed to define the transition rates and weights-of-evidence coefficients for use in the simulation. We divided some areas with similar characteristics and that had little or no influence from the BR-

319, such as Regions 8 and 9, to better represent the result in the final map without interfering with the desired result. Table S2 shows the parameters used to define the regions in this study.

Table S2 Regionalization of the study area.

Step	Justification
Region 1	Area to the east of the Madeira River that is under the influence of Highway BR-230, which is the main highway connecting to BR-319 in the southern part of the state of Amazonas. It is also influenced by the state of Pará to the east and the state of Mato Grosso to the south. It contains some of the municipalities with the highest deforestation rates in the state of Amazonas (Manicoré, Apuí, Novo Aripuanã, Humaitá), which stand out among the major cattle production in the state. It has a large area of public land with non-designated public forest, which is attractive for invasion and deforestation. It has strong activity in the wood industry.
Region 2	Area of influence to the east of the Madeira River, on the right side of the Amazon River and bordering the state of Pará. The region has livestock and lowland agriculture. It has low population density and does not have a large extension of highways and endogenous roads.
Region 3	Southern portion of the interfluve between the Madeira and Purus Rivers in the state of Amazonas. It is characterized by the influence of the BR-230, which connects the city of Lábrea to Humaitá and southern part of the municipality of Canutama. Vila Realidade (a district in the municipality of Humaitá) is located in this region, which, in recent years, has shown large increases in deforestation, land invasion and logging. The region has great influence from the state of Rondônia. It can be considered to be the region providing access from the 'arc of deforestation' to the northern portion of the state. It has strong activity of the wood industry.
Region 4	Northern portion of the Madeira-Purus interfluve in the state of Amazonas. It is heavily influenced by the state capital (Manaus) and by Highway BR-174. It is a region with large unprotected undesignated areas, as well as settlement projects that can attract migration.
Region 5	This region is characterized by the influence of the state capital, as a major consumer center. The main locations where deforestation is expanding are those with access facilitated by Highway BR-174 (Manaus - Boa Vista). The "*Zona Franca Verde*" of Manaus is present in this region, which is a program focused on attracting investment for agriculture, livestock, and tourist enterprises.
Region 6	Region of influence of the paved highways BR-364 and BR-317. The southern part of this region has high rates of deforestation, especially in the districts of Extrema and Nova California and the PA Monte and PA Antimary settlement projects. The region has a strong tendency to initiate and expand livestock production areas, especially in the municipality of Boca do Acre, the southern portion of Lábrea and in Guajara. It has strong activity of the wood industry.
Region 7	Central portion of the state of Amazonas. This is the expansion area of the planned AM-366 state highway, which proposes connecting the BR-319 to the municipalities of Coari, Tefé and Juruá. The region presents itself as an important producer of oil and natural gas. The region has few protected areas and has large areas of non-designated public forests, which favors land invasion and deforestation. The northern portion of the region has access and occupation from the Solimões (Upper Amazon) River.
Region 8	Region of influence of the Rio Negro. This region has low population density and is characterized by small towns, villages, and riverside communities. The region has extensive indigenous lands and protected areas. The main economic activity is fishing and traditional low-impact agriculture. It has an unpaved federal highway (BR-307), which connects the city of São Gabriel da Cachoeira to the town of Cucui. The region borders Colombia and Venezuela and has a strong presence of the Brazilian Army.
Region 9	Region of influence of rivers, cities, and riverside communities, indigenous lands, and protected areas. The region borders Peru and has has low population density; economic activity is mainly characterized by low-impact fishing and agriculture. It is located on the right bank the Solimões (Upper Amazon) River and is influenced by the municipality of Tabatinga on the border of Brazil with Peru and Colombia.

APPENDIX 5.

The figure below shows the parameters used to calculate the weights of evidence for the variables used in the model. Categorical variables are those that have more than one category on the same map (e.g., protected areas that have four categories: 1. Integral-protection PAs; 2. Sustainable-use PAs; 3. Indigenous lands; and 4. Military areas). This is in contrast to variables that are not categorical and present only one item of information, without subdivisions (road map, deforestation map, and hydrographic map).

Table S3 Parameters for calculating weights of evidence.

Identifier	Categorical	Increment	Min. Delta	Max. Delta	Tol. Angle
distance_roads	no	100	1	5,000,000	5.0
distance_deforestation	no	100	1	5,000,000	5.0
static_var					
distance_Hydrography	no	100	1	5,000,000	5.0
Protected_areas	yes				
settlements	yes				

For the definition of weights of evidence, the DINAMICA-EGO model makes the calculations and defines the distances based on the input maps. However, in the calibration stage, these data can be adjusted in order to achieve the best representation of what is to be modeled (Soares-Filho *et al*., 2009). In the present study the interval was adjusted and fixed at 100 m, based on the spatial resolution adopted in the study.

Regarding the definition of the influence distances of non-categorical variables, several tests were performed to define the best result in the validation. The distance that best represented the similarity in the comparison of the simulated deforestation map of 2021 with the real deforestation from PRODES in 2021 was 1500 m. Fig. S3 shows the non-categorical variables with an interval of 100 m and a distance of influence of 1500 m. It is worth mentioning that in this study adjustment was only done for the intervals and distances of influence, with no numerical adjustment of the weights-of-evidence coefficients.

```
:dist_roads/distance_to_1    0:100    100:200    200:300    300:400    400:500    500:600    600:700    700:800    800:900    900:1000    1000:1100    1100:1200    1200:1300    1300:1400    1400:1500
2,1    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0

:distance/distance_to_1    0:100    100:200    200:300    300:400    400:500    500:600    600:700    700:800    800:900    900:1000    1000:1100    1100:1200    1200:1300    1300:1400    1400:1500
2,1    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0

:static_var/hidro    0:100    100:200    200:300    300:400    400:500    500:600    600:700    700:800    800:900    900:1000    1000:1100    1100:1200    1200:1300    1300:1400    1400:1500
2,1    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0

:static_var/protected_areas    0:1    1:2    2:3    3:4    4:5
2,1    0    0    0    0    0

:static_var/settlement    0:1    1:2    2:3    3:4    4:5    5:6    6:7
2,1    0    0    0    0    0    0    0

```

Fig. S3 Adjustment of the intervals and distance of the skeleton used to calculate the weights-of-evidence coefficients in the model that best represented the real PRODES_2021 map in relation to the simulated one in the validation model.

Regarding the methodology for applying the deforestation rate, it was decided to survey the average increase and decrease (Md_i and Md_d) in the period from 2000 to 2014 to better represent the trends of increase and decrease in the simulation from 2014 to 2021, as can be seen in Fig. S4. For the increase, the average of all the years in which deforestation was positive in relation to the previous year was calculated. The corresponding average was calculated for the decreases.

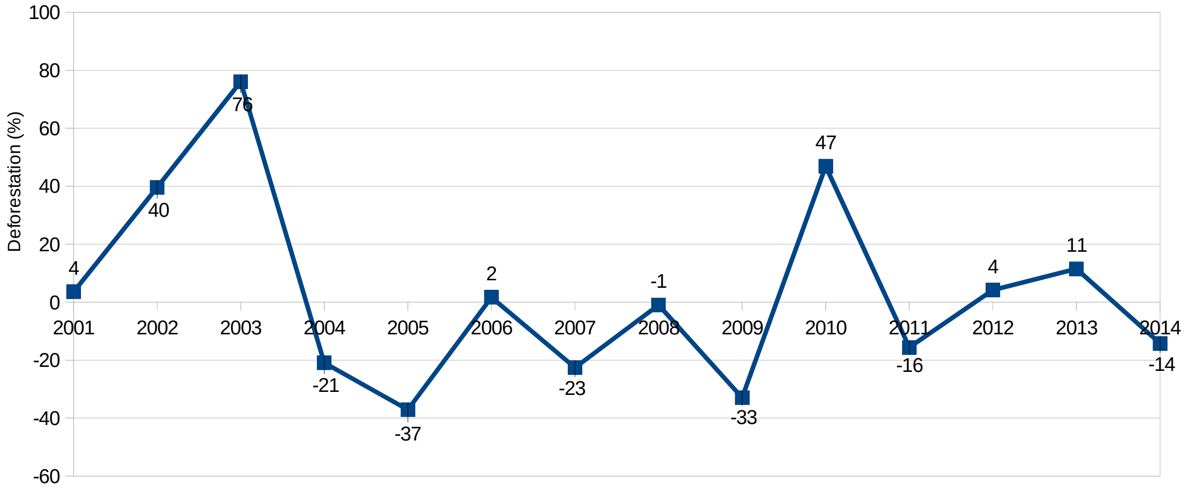


Fig. S4 Percentages of increase and decrease of deforestation in relation to the previous year for the state of Amazonas. Where the average increase corresponds to 26.2% and the average decrease to 20.6% for the period from 2000 to 2014.

The same principle was used to simulate the scenarios from 2021 to 2100, with the goal of updating the index to better represent the trend of increase and decrease up to 2021, which was the year of the beginning of the scenario simulation (Fig. S5). However, it was decided to maintain the input transition rates used in the calibration, considering that the model presented a satisfactory result in the validation, as shown in Table S5.

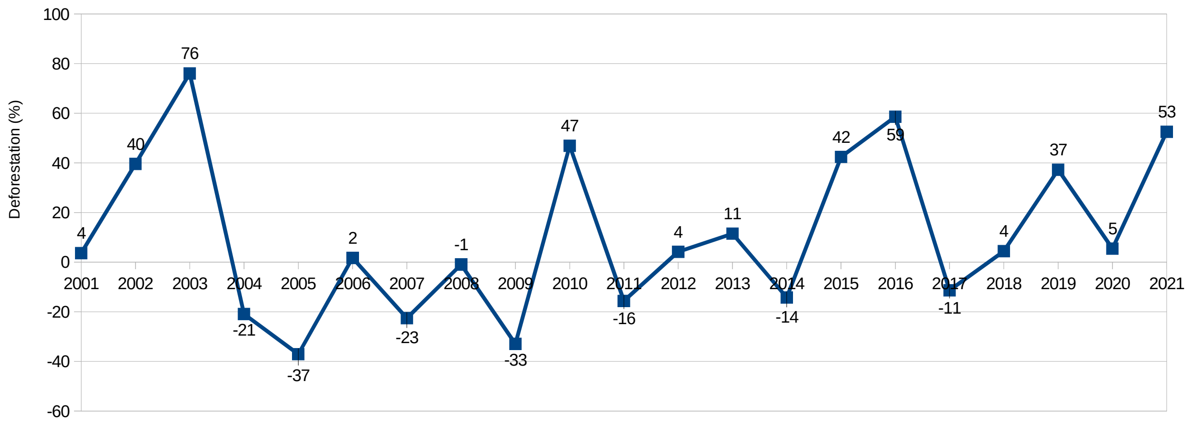


Fig. S5 Percentages of increase and decrease of deforestation in relation to the previous year for the state of Amazonas, where the average increase corresponds to 31.6% and average decrease to 19.5% for the period from 2000 to 2021.

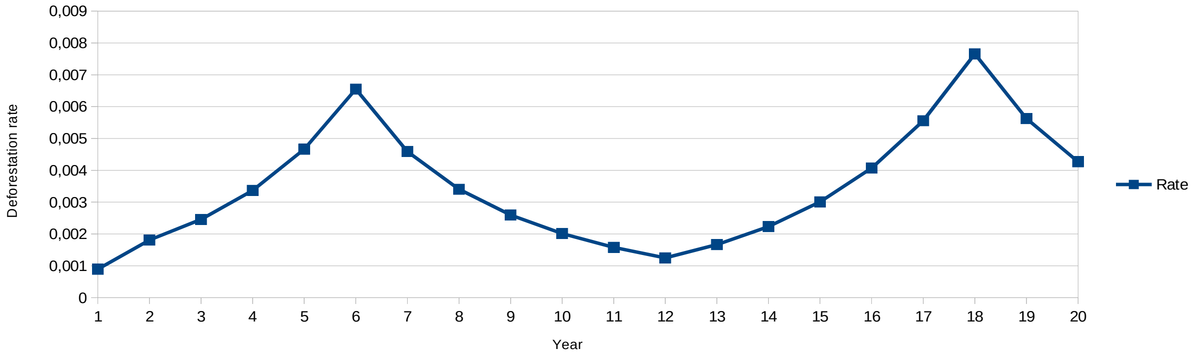


Fig. S6 Example applied to demonstrate the fluctuation of the deforestation rate over the intervening period of 6 years.

Tabela S4 Data used to calculate annual deforestation rates for simulation from 2014 to 2021.

Regions	Average Rates of Transition 2007 - 2013	Index of Transition (%)	Deforestation cumulative up to 2007 (km^2)	Deforestation cumulative up to 2013 (km^2)	Forest area available in 2007 (km^2)	Forest area available in 2013 (km^2)
Region 1	0.0008937	50.59	4,168.97	5,194.10	198,443.96	197,418.83
Region 2	0.0005672	29.39	4,948.60	5,116.53	42,958.80	42,790.87
Region 3	0.0007987	38.30	2,931.67	3,292.34	75,413.77	75,053.10
Region 4	0.0007379	32.37	4,103.92	4,365.23	59,124.14	58,862.83
Region 5	0.0004074	30.74	6,984.21	7,315.11	135,521.33	135,190.43
Region 6	0.0008912	36.43	12,626.69	13,943.21	246,743.18	245,426.66
Region 7	0.0001413	30.85	2,045.33	2,144.46	116,939.81	116,840.68
Region 8	0.0000469	30.08	3,050.72	3,175.21	442,870.26	442,745.77
Region 9	0.0000608	31.13	1,596.85	1,678.69	224,457.00	224,375.16

Table S5 Data used to calculate annual deforestation rates for simulation from 2021 to 2100.

Regions	Average Transition Rates 2007 - 2013	Index of Transition %	Deforestation cumulative up to 2014 (km^2)	Deforestation cumulative up to 2021 (km^2)	Forest area available in 2014 (km^2)	Forest area available in 2021 (km^2)
Region 1	0.0008937	102.41	5,345.78	9,109.74	197,267.15	193,503.19
Region 2	0.0005672	35.01	5,147.07	5,302.04	42,760.33	42,605.36
Region 3	0.0007987	66.16	3,331.46	4,469.53	75,013.98	73,875.91
Region 4	0.0007379	39.42	4,388.07	4,713.67	58,839.99	58,514.39
Region 5	0.0004074	35.85	7,352.00	7,634.83	135,153.54	134,870.71

Region 6	0.0008912	65.34	14,279.09	19,040.05	245,090.78	240,329.82
Region 7	0.0001413	38.42	2,182.20	2,322.31	116,802.94	116,662.83
Region 8	0.0000469	36.20	3,193.15	3,327.30	442,727.83	442,593.68
Region 9	0.0000608	40.05	1,689.40	1,825.68	224,364.45	224,228.17

APPENDIX 6.

Table S6 Patcher and expander allocation according to sub-region.

Region	**From**	**To**	**Mean_Patch_Size (ha)**	**Patch_size_Variance (ha)**	**Patch_Isometry**
1	Forest	Deforestation	11	34	1.5
2	Forest	Deforestation	5	15	1.5
3	Forest	Deforestation	8	24	1.5
4	Forest	Deforestation	6	18	1.5
5	Forest	Deforestation	5	15	1.5
6	Forest	Deforestation	7	21	1.5
7	Forest	Deforestation	5	15	1.5
8	Forest	Deforestation	5	15	1.5
9	Forest	Deforestation	5	15	1.5

APPENDIX 7.

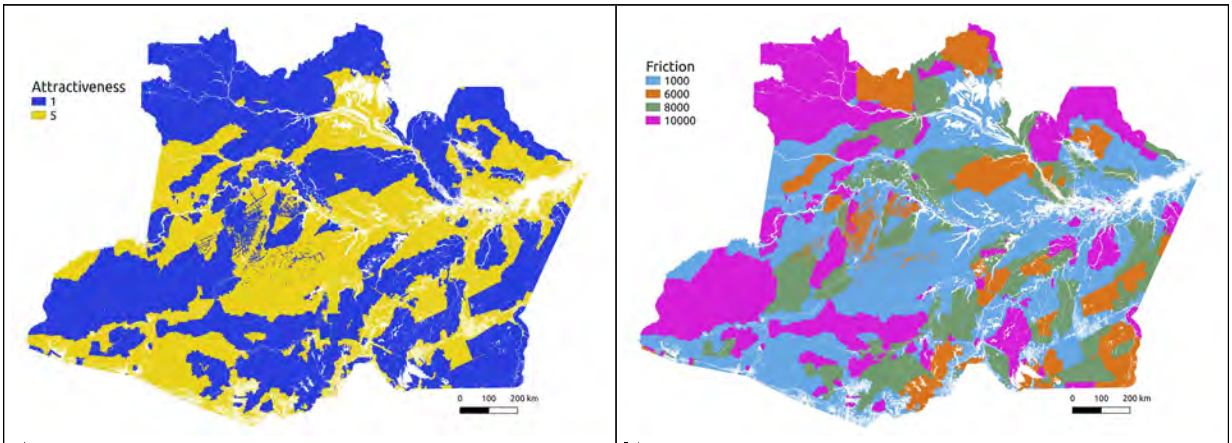
To guide the construction of roads in the model, it was necessary to insert an attractiveness map (with areas that are favorable to building roads) and a friction map (with resistance to building roads). For this, a sub-model of DINAMICA-EGO was used that multiplies the values assigned to the classes of each input map (Land cover 2013 and Land categories 2013) and, as a result, friction and attractiveness maps were obtained (Table S7).

Considering that the model's focus is deforestation, "non-forest" (savannas, water, rocky outcrops, etc.) and "deforestation" (previously deforested area) were assigned a value of zero in both maps (a zero value does not generate a road). The higher the value for attractiveness, the greater the possibility of the model building roads; therefore, value 1 was assigned to "forest" in the "land cover" map, and 5 for "non-protected areas" in the map of "land categories," while the other classes were kept with the value 1 (Table S7). The highest value (5) makes unprotected areas highly attractive to road construction (Fig. S7a); however, roads will only be built in these areas in the model if the value for the land category is non-zero, that is, if the area is in forest.

Friction is based on the same principle, and the higher the friction value for a land-cover class, the greater the resistance for road construction (Table S7). "Military areas" and "indigenous lands" were assigned the highest friction value (10,000) "Integral-protection protected areas" were given a friction value of 8000, and "sustainable-use protected areas" received a value of 6000, while "non-protected areas" received a value of 1000. These values can be assigned by the modeler, representing what the modeler considers to be the relative difficulty of building roads in areas of different land categories. For example, it is easier to build a road in a sustainable-use conservation unit than in an indigenous land. We arrived at these values after they gave the best result in several validation tests. The combination between the maps made the model define where to allocate the roads based on the highest value of attraction and lowest value of friction (Fig. S7b).

Table S7 Values assigned for the construction of attractiveness and friction maps used for road construction in the model.

Map	Map component	Attractiveness	Friction
Land cover 2013	Non-forest	0	0
	Deforestation	0	0
	Forest	1	1,000
Land categories 2013	Non-protected area	5	1
	Sustainable-use protected areas	1	6
	Integral-protection protected areas	1	8
	Indigenous lands	1	10
	Military area	1	10



a) Attractiveness map
b) Friction map

Fig. S7 Map of attractiveness (a) and friction (b). These values are the result of the interaction between the “land cover” and “protected areas” maps.

APPENDIX 8

Null Model - Simply put, the model makes the comparison through window sizes, that is, with the number of cells corresponding to the resolution used in the modeling. For example: in this study the resolution adopted was 100 m, so window 1 (1 × 1) corresponds to 100 m × 100 m (0.01 km^2), window 3 (3 × 3) = 300 m × 300 m (0.09 km^2), and so on. Because the comparison is made using both maps (simulated and observed), the results can generate rates with minimum and maximum similarity values, which can vary from 0% to 100% (0% indicates that the maps are completely different and 100% indicates they are identical). In this study we adopted the minimum similarity value as a reference. We compared the simulation results with a null model, which uses the same maps and input rates but with weights-of-evidence values set to zero. The null map was also compared with the observed map (PRODES 2021). To be considered efficient, the proposed model must win in all comparisons made with the null model.

Table S8 Projected deforestation in relation to real deforestation.

	km²	Difference %	Difference in km²	Cumulative Deforestation in the study area up to 2021 km²
Simulated deforestation study area in 2021	57.431,23	-0,54	-313,92	57,745.15

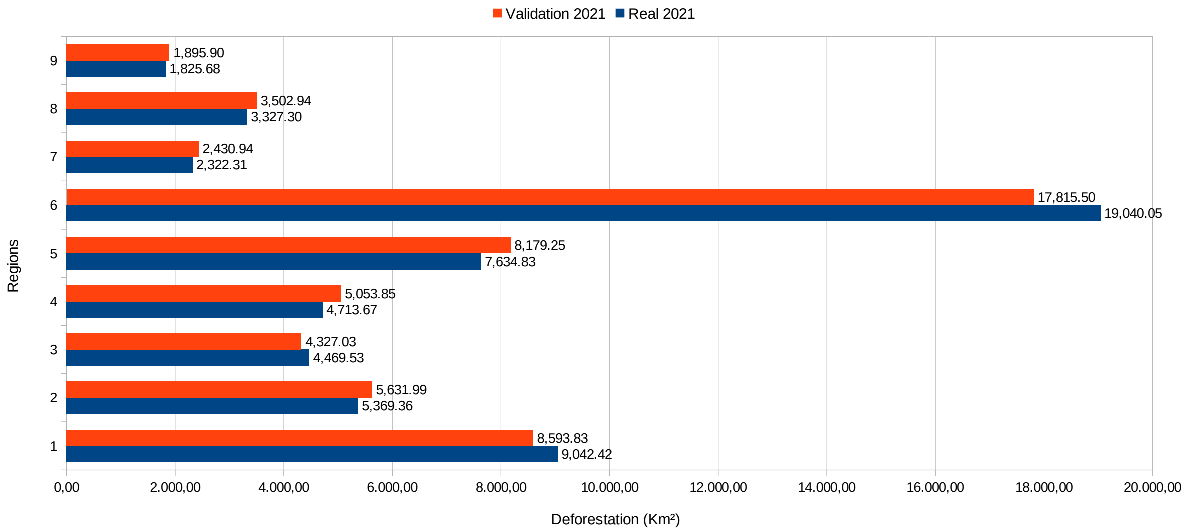


Fig S8 Projected deforestation by region in relation to 2021 deforestation.

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