Ramos, C.J.P.; P.M.L.A. Graça & P.M. Fearnside. 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**

DOI: 10.1007/s00267-018-1097-3

ISSN: 0364-152X

Deforestation dynamics on an Amazonian peri-urban frontier: Simulating the influence of the Rio Negro Bridge in Manaus, Brazil

1. ABSTRACT

Peri-urban expansion is an increasingly important source of tropical deforestation, and a bridge over the Rio Negro in Brazil's state of Amazonas provides an unusual opportunity to quantify these impacts with clear "before" and "after" periods. Inaugurated in 2011, the bridge connects Manaus to forest areas on the right bank of the river, thus opening a new frontier for peri-urban expansion. We used the AGROECO model in the Dinamica-EGO software to simulate "Bridge" and "No-bridge" scenarios to evaluate the spatial dynamics of deforestation in the municipalities (counties) of Iranduba, Manacapuru and Novo Airão. Simulated deforestation between 2011 and 2030 for the study area as a whole was 106% higher with the bridge. The portion of the study area with expansion of roads had four times more deforestation in the Bridge scenario than in the No-bridge scenario. A change in the spatial distribution of the deforested area was detected, with an advance of deforestation in the municipality closest to the bridge. Deforestation also expanded in more distant regions. Peri-urbanization in the Bridge scenario demonstrates the possible increase in the spatial distribution of deforestation activity beyond the already-consolidated frontier, making the deforestation pattern more diffuse and leaving the remaining forest even more vulnerable. Impact of the bridge could further increase due to additional factors, such as the planned opening of a highway (BR-319) connecting Manaus to Brazil's "arc of deforestation."

Keywords: Amazon; deforestation; land-use change; urbanization; peri-urbanization; Brazil

Highlights

Completion of Brazil's Rio Negro Bridge in Manaus in 2011 allows urban expansion.

Simulated deforestation to 2030 in the area accessed is 106% higher with the bridge.

Clearing on the Rio Negro's right bank is more spatially dispersed with the bridge.

A planned highway link to the arc of deforestation could further accelerate clearing.

1. Introduction

Urbanization is rapidly progressing in the Amazon region. In 2010 the Brazilian Amazon had 71% of its population in urban areas (Brazil, IBGE 2016a), and urbanization has become a major environmental problem in the Amazon due to rapid migration and lack of infrastructure (Becker 2001). Amazon deforestation represents one of the world's great environmental problems, and understanding its multiple causes is a high research priority on a global scale. Urban growth has been one of the most powerful forces in worldwide landscape change in recent decades (Su et al. 2014; Wang and Qiu 2017), and this impact is expected to increase dramatically by 2030 (Forman and Wu 2016). Urban areas are expanding into the countryside, a phenomenon known as "peri-urbanization." Peri-urban areas are characterized by having urban, rural and natural elements at different levels. The landscape is not static, but rather changes over time (Allen 2003; Moreira et al. 2016).

Interaction between an urban area and its associated peri-urban area is determined by factors such as population density, availability of roads, land use and territorial planning (Tacoli 2003). Increased mobility can intensify income-generating activities by allowing commuting between these areas; examples of these relations include interchange between agricultural producers and urban markets and increasing real-estate speculation for residential and recreational uses (e.g., Yu and Ng 2007). It is therefore expected that an abrupt improvement of the transport network connecting an urban center to its surroundings can cause major changes in land cover. Urban growth can be classified into three types: “infilling” (increasing population density in the existing urban area), “edge-expansion” (urbanization advancing from the edges of an existing urban area) and “outlying” (emergence of new urban patches that are isolated from existing urban areas) (Shi et al. 2012). In the case of an outlying area being connected to an urban center by improving a road network, the process becomes one of edge expansion and thus increases the potential for the spread of urban areas.

Manaus (2016 population 2.1 million: Brazil, IBGE 2017) is located in central Amazonia near the confluence of the Rio Negro and the Upper Amazon (Solimões) River. The city has grown rapidly as a free-trade zone where factories assemble products from imported components. The Rio Negro, one of the world’s largest rivers, has served as a barrier blocking expansion of the city to the south. The Rio Negro Bridge, inaugurated on 24 October 2011, eliminated this barrier (Figure 1). The Rio Negro Bridge presents an unusually clear case for assessing the peri-urbanization process. In most cases, peri-urbanization spreads gradually in concentric circles as a city grows, thereby not providing clear “before” and “after” periods. In the case studied here, however, the building of a bridge suddenly opened the floodgates to peri-urban expansion from Amazonia’s largest city.

[Fig._1_here]

Deforestation on the right bank of the Rio Negro can be expected to increase due to factors such as the population growth of Manaus (Supplementary material, Figure S-1), construction of a university center in the municipality of Iranduba, widening the AM-070 road, and expanding existing activities in brick and tile production, as well as the announcement of plans for a variety of other projects (Moreira et al. 2009; Rodrigues et al. 2014; Sousa 2015). There is also a plan to rebuild Highway BR-319, a road that has been abandoned since 1988 and, if reopened, would connect the Manaus area to Brazil’s notorious “arc of deforestation” in southern Amazonia, thus facilitating migration and increasing deforestation (Fearnside et al. 2009; Soares-Filho et al. 2006, Nepstad et al. 2011). Roads represent one of the main drivers of Amazonian deforestation (Fearnside 2017a,b; Kirby et al. 2005; Laurance et al. 2002; Souza Jr. et al. 2005), and 95% of the deforestation in Brazilian Amazonia occurs within 5.5 km of a road (Barber et al. 2014). Added to these factors, the urban zone of Manaus is compressed between the Tarumã-Açu River, the Adolpho Ducke Forest Reserve and the Rio Negro (Supplementary material, Figure S-2). The Rio Negro Bridge has raised demand for property on the right bank of the river, increasing the value of urban land and fueling real-estate speculation (Sousa 2015). Interest is no longer only focused on agricultural production, but the area still lacks many urban attributes, leading to low population density and a lack of services and infrastructure (Allen 2003).

The objective of this study was to evaluate the spatial dynamics of deforestation resulting from an infrastructure project that connects an area of peri-urbanization to a major city. This evaluation, which is based on the comparison of scenarios with and without the bridge, allows assessment of how different patterns of land-cover change can occur through "outlying" and "edge-expansion" dynamics in peri-urban areas. Our study simulates the effect of the Rio Negro Bridge on deforestation in the municipalities of Iranduba, Manacapuru and Novo Airão through 2030.

Deforestation in Amazonia has a wide variety of environmental impacts, including site degradation through soil erosion and other processes, loss of biodiversity and loss of the forest’s functions in maintaining climatic stability by storing carbon and by recycling water that supplies rainfall both in Amazonia and in other parts of Brazil and neighboring countries (Fearnside 2017a,b). The gravity of these impacts makes advances in our ability to model the deforestation consequences of different development decisions an important priority not only for Amazonia but also for other parts of the world.

2. Methods

2.1. Study area

The municipalities of Iranduba (land area of 2214 km^2), Manacapuru (7330 km^2) and Novo Airão (37,771 km^2) are located in the Manaus Metropolitan Region, in Brazil’s state of Amazonas (Figure 1). The estimated 2016 populations of these municipalities were 46,703, 95,330 and 18,133 inhabitants, respectively (Brazil, IBGE 2016b). The municipality of Novo Airão is bisected by the Rio Negro and Manacapuru is bisected by the Upper Amazon (Solimões) River, while all of Iranduba is in the wedge of land between these two great rivers (Figure 1). The study area is restricted to the area under direct influence of the bridge, which corresponds to the wedge of land between the right bank of the Rio Negro and the left bank of the Upper Amazon (Solimões). This area was bounded by a 30-km buffer around the main roads: AM-070 and AM-352 (Figure 2A).

[Fig_2_here]

The main economic activity in the three municipalities is farming (temporary and permanent), followed by pasture (Fernandes 2013). Land use is characterized as a mosaic of occupations for family agriculture and livestock. In addition, these municipalities, especially Novo Airão, have long had ecotourism as a major activity.

The study area was divided into “regions” (regionalized) according to road density in the period from 2004 to 2014. The study area is extensive and has a variety of peculiarities, making regionalization necessary in order to capture the different spatial characteristics of deforestation (Figure 2A). The simulation was run individually for each region of the study area. The density of roads provides a means of distinguishing the five regions. First, a 1-km buffer was delimited around the great rivers. This buffer denominated "River access" represents the influence of the main water bodies as transportation connections to these areas. The remaining area was divided into regions according to road densities calculated as the length of roads per unit area (km/km^2). Increase in roads in this period differed among the regions, which were therefore ranked according to road density as well as according to the increase in roads. Additionally, field observations were undertaken for reconnaissance of the study area and to gain an understanding of changes in land cover (Supplementary Material, Appendix 1).

2.2. The AGROECO Model

The methodological steps in the study are summarized diagrammatically in the Supplementary Material (Figure S-3). We simulated deforestation from 2011 to 2030 under “Bridge” and “No-bridge” scenarios using the AGROECO spatial model developed by Fearnside et al. (2009), which is implemented in Dinamica-EGO software (Rodrigues et al. 2007; Soares-Filho et al. 2002, 2009). The model is based on cellular automata, which represent the dynamics of a system as a grid. Each cell of an *n*-dimensional system of cells will have its state updated in discrete steps based on a set of transition rules that are specified in accord with a particular neighborhood (Soares-Filho et al. 2002, 2007). Cellular-automata models are tools with great potential for understanding urban dynamics because they integrate spatial and temporal dimensions of these dynamics (Santé et al. 2010). Spatial predictive models simulate the alteration of environmental attributes, thus helping to understand the causal mechanisms and the dynamics of environmental systems (Soares-Filho et al. 2007).

The basis of the AGROECO model (Supplementary Material, Figure S-4) is that at each iteration (repetition of the model calculations) updates a map of the “accessible” land surface, delimiting the forest area available for deforestation. This surface increases as the road network expands. New simulated roads are built by the road-building module in the software. At each iteration this module incorporates likely new roads into the simulated map of the area. Rates of deforestation in the annual simulations fluctuate due to deforestation being stimulated through extension of the road network, which increases the area available to deforestation.

2.3. Input data for the spatial model

Ecosystem services, here represented by forests, have an essentially spatial nature, thus requiring representation with maps (Swetnam et al. 2011). Maps of land cover from 2004 to 2010 were prepared for the study area from PRODES deforestation data (Brazil, INPE 2018). PRODES is the Project for Monitoring the Brazilian Amazon Forest by Satellite, through which the National Institute for Space Research (INPE) maps Brazil’s Amazonian deforestation annually. The minimum area of deforestation mapped by PRODES is 6.25 ha. We used the UTM [Universal Transverse Mercator] map projection with UTM Zone 20 S and Datum WGS [World Geodetic System] 1984. In the processes of calibration and simulation the spatial resolution adopted was 120 m, and the data were in raster format.

The set of variables used can be seen in the Table 1. The variables examined represent a set of spatially determined social and biophysical factors. Some of the variables used are static and do not change with every iteration. Distance to municipal seats is an indicator of population and a proxy for local markets (Aguiar et al. 2007). Dynamic variables were also used that are updated in each iteration of the model and are displayed in the form of maps.

[Table_1_here]

Maps of “attractiveness” for roads and “friction” impeding road construction were generated in the Dinamica-EGO software, as described by Soares-Filho et al. (2009). The attractiveness map provides input to the calculation of target cells for building roads, and the map is built based on characteristics of the area that act as attractions to human activities such as proximity to existing roads and to previously cleared areas. Similarly, the combination of maps for protected areas (conservation units and indigenous lands) was used to create the friction map to identify the least-cost pathway to construct each new road (see Supplementary Material, Appendix 2). The values adopted (following these weightings) are presented in the Supplementary Material (Table S-1). Thus, the roads are automatically placed in accordance with the level of attractiveness and the cost of constructing a road.

2.4 Calibration

2.4.1 Periods used to calibrate the scenarios

The calibration phase is the stage when model parameters are fit to achieve the best match between the simulated model and the PRODES deforestation data in the calibration period for each scenario. The model was calibrated based on historical dynamics of deforestation in the study area itself. The dates used in each scenario are summarized in Table 2. The No-bridge scenario used rates of deforestation between 2004 and 2006, a period when the bridge neither existed nor was under construction. The Bridge scenario considered the deforestation rates from 2008 to 2010, since construction of the Rio Negro Bridge began in December 2007 and land-cover dynamics changed significantly after that event.

[Table_2_here]

The periods used are short (Supplementary Material, Appendix 3). However, data from PRODES (Brazil’s official deforestation monitoring program) are available only beginning in 2000. The deforestation rate was extremely high at the beginning of the 2000s both for the study area and for surrounding municipalities. In Amazonia as a whole deforestation dropped precipitously after 2004, but in the study area the major drop began in 2002, and from 2004 to 2008 the rate declined slightly but remained relatively stable. After 2008 there was a sequence of pulses of the deforestation rate (Supplementary Material, Figure S-5). We therefore only used the years immediately prior to the start of bridge construction as the reference for the "No-bridge" period. Because three years was used for the reference period for the "No-bridge" scenario (2004-2006), a period of the same three-year length (2008 -2010) was used as the reference period for the Bridge scenario. The years after construction of the bridge began (i.e., 2008 onwards) show a sequence of pulses in the deforestation rate, suggesting an intense dynamic in progress in the region. This kind of accelerated deforestation activity in anticipation of implanting new infrastructure has occurred repeatedly in the case of Amazonian highway projects, such as the BR-163 (Santarém-Cuiabá) and BR-319 (Manaus-Porto Velho) highways (Fearnside 2007; Fearnside and Graça 2006). A recent effect of this kind was unleashed by announcement of plans to remove protection from parts of some conservation units along the BR-163 Highway, leading to a surge of invasion and deforestation in these areas (Branford and Torres 2017).

The deforestation rate in each year is subject to many factors besides the existence of a bridge, include major economic cycles, electoral cycles and variations in the effort applied to enforcing environmental restrictions. Deforestation rates in Brazilian Amazonia as a whole underwent a prolonged decline from 2004 to 2012 for a combination of reasons (e.g., Fearnside 2017a,b). If the No-bridge scenario were to use the early 2000s as a baseline, this scenario would be based on parameters for a period with a substantially higher average deforestation rate than the baseline used for the Bridge scenario, thereby artificially making the bridge appear to have a beneficial effect in slowing deforestation. On the other hand, a spurious result would also occur if the No-bridge scenario were to use as a baseline the three-year period when the bridge was under construction but not yet completed (i.e., 2008-2010) because this period had an increased rate of deforestation due to the rapid rise in real estate values and resulting land speculation. The year 2008 marks the beginning of the influence of the bridge.

2.4.2 Weights of evidence

The weights-of-evidence statistical method is applied in the model to produce probability maps for land-cover transitions that represent the most favorable areas for change (Soares-Filho et al. 2007, 2009). This Bayesian method calculates the *a posteriori* probability of an event occurring (in this case, deforestation) given an *a priori* condition favorable to the event (Bonham-Carter et al. 1989). Coefficients of the weights of evidence represent the influence of each category (range of values) of a given variable in changing land cover, in this case the transition from forest to deforestation. The first step was to map this change in land cover. For the No-bridge scenario, the 2004 land-cover map was compared to the 2006 map, and for the Bridge scenario the 2008 land cover was compared to the 2010 map. Next, changes were detected between these maps and related to the variables. For example, each soil type received a weight of evidence for deforestation (Supplementary Material, Figure S-6). For the application of the method of weights of evidence, the maps of the input variables must be spatially independent. The correlation maps of the input variables were tested using the method included in Dinamica-EGO software (Supplementary Material, Appendix 4).

2.4.3 Deforestation rate

The transition rate is the number of cells that change by moving from one category to another within a single iteration. In this study the transition rate is the annual rate of deforestation expressed as number of cells per year. This rate was calculated from the equation of Yanai et al. (2012), which uses a concept of "agrarian forest surface" (AFS) to represent the importance of roads in facilitating occupation by smallholders along these roads (Fearnside et al. 2009). A 2-km buffer on each side of the roads was used as the AFS for calculating deforestation rates in this zone for each region during the period used for calibration of each scenario. The year 2010 was used to calibrate the scenarios, so this was the year selected for assigning the buffers around roads in order to calculate the annual deforestation rates in the ASF for each calibration period. For each scenario the annual deforestation rate was calculated for each calibration period from the areas of forest and the deforestation data inside and outside of the agrarian forest surface (Table 3). The ratio of average annual deforestation to the annual average forest area within the AFS provides a proportion, which represents a relative rate of deforestation. These calculations are also performed for the area outside of the AFS (Supplementary Material, Table S-2). In the simulation these proportions were used in the transition-rate equation that calculates the conversion of forest to deforested cells in each iteration (Equation 1).

$$\mathbf{R} = \frac{(\mathbf{A}_{\mathbf{AFS}} \times \mathbf{P}_{\mathbf{AFS}}) + (\mathbf{A}_{\mathbf{out}} \times \mathbf{P}_{\mathbf{out}})}{\mathbf{A}_{\mathbf{AFS}} + \mathbf{A}_{\mathbf{out}}} \qquad \textbf{Eq. 1}$$

Where:

R = Rate of deforestation (ha cleared per year)

A_{AFS} = Area of the agrarian forest surface (ha)

P_{AFS} = Deforestation proportion for the agrarian forest surface (proportion of remaining forest cleared per year)

A_{out} = Area outside of the agrarian forest surface (ha)

P_{out} = Deforestation proportion for the area outside of the agrarian forest surface (proportion of remaining forest cleared per year)

[Table_3_here]

Since the map of simulated roads is updated in every iteration, the forest areas available inside and outside of the AFS are also changed. Thus, the deforestation rate is updated in every iteration.

Dinamica-EGO converts the deforestation simulated between two functions: the “Expander” and the “Patcher” (Soares-Filho et al. 2009). The Expander makes simulated deforestation occur as an enlargement of clearings that have already been initiated, while the Patcher creates new clearings, thereby initiating new deforestation foci in the landscape. Both functions have input parameters for adjusting the isometry, variance and average size of patches of clearing (Soares-Filho et al. 2007). These parameters are set in the model calibration phase for each scenario.

2.5. Validation

The validation step provides a measure of how well model results match observations in the real world, and thus whether it is appropriate to proceed with the analysis. To validate the amount of change, the numbers of cleared cells were compared between the simulated and observed maps for the five regions in each scenario (Supplementary Material, Table S-3). For the No-bridge scenario the simulated and observed land-cover maps were for 2006, while for the Bridge scenario these maps were for 2010. Initially, there was a 7.9% validation error for deforestation in the study area as a whole for each scenario. The transition-rate calculation uses the concept of "agrarian forest surface," which highlights the importance of roads in making the forest accessible to human activities, but several new roads have been built that have only recently been occupied. This explains the 7.9% underestimation of the deforested area in the simulation in the first validation. The underestimate meant that the representation of deforestation was conservative; we therefore made a correction of the average annual net rate of deforestation to attenuate this effect. These rates were updated (Supplementary Material, Table S-4) based on the percentage error of the deforestation projection specific to each region (Supplementary Material, Appendix 5). The No-bridge scenario yielded a -0.09% error and the Bridge scenario a 0.32% error for the entire study area. Validation for each region after the updating of rates was also acceptable in both scenarios (Supplementary Material, Table S-3).

The model’s spatial performance underwent validation by comparing a simulated map with a map of deforestation observed by PRODES for the same year. The test used was the fuzzy similarity method, which considers allocations and categories within a neighborhood (Hagen 2003). Dinamica-EGO calculates the similarities in a neighborhood with different sizes of windows of cells, starting with windows of 1 × 1 cell and proceeding up to 19 × 19 cells. The indices of similarity between the real and the simulated maps can vary from being totally different (value = 0) to identical (value = 1). The value obtained was approximately 50% similarity for the 11 × 11 cell window for both scenarios (Supplementary Material, Figure S-7). The deforestation pattern in the study area was diffuse in both periods used for calibration; deforestation patches are allocated at several points (Supplementary Material, Figure S-8). These new patches are small, which further complicates the validation of the distribution of deforestation.

3. Results

3.1. Regionalization of the study area

The five regions in the study area could be distinguished based on ease of access, four based on the density of roads and the fifth based on river access. A decreasing gradient of road density with distance from Manaus is apparent (Figure 2B).

Region A (High road density), despite receiving a heavy influx of population, had only 22% growth in its road network between 2004 and 2014 (the period of road mapping) -- the second lowest percentage for the entire study area. Region A is an area that was formerly populated and so had an extensive road network since the beginning of our mapping of roads (2004). Region A is the densest region, with 1.43 km roads/km². This region has a consolidated road-network profile because it encompasses the municipal seat of Iranduba and is also the closest to Manaus.

Region B (Average road density) -- the second-densest region, with 0.65 km roads/km² -- encompasses the municipal seat of Manacapuru. The Average road-density region had a slightly higher growth percentage (25%) than the High road-density region, since the process of road expansion is still underway. It was characterized as an area in the process of consolidating its road network.

Region C (Low road density) is the third densest region, with 0.27 km roads/km². This region lacks any municipal seats, is far from densely populated areas and features large areas of forest. This region had the greatest percentage increase (145%) in the density of roads. This area still shows great potential, both in terms of available area and in the recent increase in road-network expansion, so it was designated as an area in the process of expanding road density.

Region D (Very low road density) is the region with the lowest road density, with 0.06 km roads/km². This region had the second-fastest growth in percentage terms. However, since road density is still very low in absolute terms, the potential for expansion of roads and deforestation within the simulation time frame is also lower as compared to the other regions. The Very low road-density region includes the municipal seat of Novo Airão, which has the smallest population of the three municipalities of the study area. Novo Airão has large areas of forest and its economy is based on ecotourism. This is therefore an area with potential for road expansion.

Region E (River access) is the area within 1 km of the great rivers. This region had the smallest percentage growth in the density of roads: 18.1%. However, because this region is located next to the great rivers, it is easily accessible and permeable. This region has 0.13 km roads/km². This area has the greatest accessibility, as it has both the road network and transport by river.

Calculation of the percentage of available area of forest for each region was based on the year 2011 -- the beginning year of the simulation. The Very low road-density region has the highest percentage of forest (98%), and the High road-density region has the lowest percentage (25%). The Average road-density, Low road-density and River-access regions had 61.6%, 92.4% and 65.9% of their areas in forest, respectively.

In 2010, the entire study area had a deforested area of 90,694 ha, with the “High,” “Average,” “Low,” and “Very low” road-density regions and the “River access” region having 31,423, 18,247, 8915, 2509 and 29,597 ha, respectively. These values are derived from deforestation data available from PRODES based on 30-m resolution Landsat-TM (Land Remote-Sensing Satellite-Thematic Mapper) imagery (Brazil, INPE 2018). The historical sequence of annual deforestation rates is detailed in the Supplementary Material (Appendix 6 and Figure S-9).

There are three protected areas in the study area; one (Anavilhanas National Park) is classified as “integral protection” (IP) and the other two as “sustainable use” (SU): The Rio Negro Right Bank Environmental Protection Area (EPA) and Rio Negro Sustainable Development Reserve (SDR) (Supplementary Material, Figure S-10). By 2010, two of the conservation units had much of their territories in the study area considered as deforested (Anavilhanas National Park and Rio Negro Right Bank EPA, with 32 and 24%, respectively), while the Rio Negro SDR, had only 6% deforested. This protected area was created in 2008, whereas the EPA and SDR were created in 1995 and 1981, respectively.

3.2. Simulation of deforestation for both scenarios

Simulated deforestation for the No-bridge scenario from 2011 to 2030 for the study area as a whole totaled 15,426 ha (Figure 3). The High road-density region had 2934 ha deforested over this period, while the Average road-density region had 2548 ha, the Low road-density region had 3322 ha, the Very low road-density region had 2093 ha, and the River-access region had 4527 ha.

One can see the same spatial pattern in all regions for the No-bridge scenario (Figure 4A). The spatial distribution of simulated deforestation showed that the majority is concentrated in areas with prior clearing (Deforestation by 2011). Deforestation is concentrated in the area closest to the city of Manaus and near the municipal seats in the study area (Figure 4B).

[Figs_3_ & _4_here]

Over the 2011-2030 period, deforestation in the Bridge scenario was 31,790 ha, which represents 106% more than the No-bridge scenario (Figure 3). For the High road-density, Average road-density, Low road-density, Very low road-density and River-access regions the cumulative areas of deforestation in the period were 3944, 2445, 16,391, 3193 and 5816 ha, respectively (Figure 3). For this scenario, these values represent increases of 34%, 393%, 52% and 28%, respectively. Only the Average road-density region had more deforestation in the No-bridge scenario than in the Bridge scenario, with 4% more deforestation occurring in this region in the No-bridge scenario than in the Bridge scenario in this period.

The simulated deforestation was also allocated to locations near previously deforested areas (Deforestation by 2011) in the Bridge scenario (Figure 4C) as well as in the No Bridge scenario. However, there is an unusual variation in the Bridge scenario in relation to the No-bridge scenario, with deforestation occurring in areas with little previous deforestation along the new roads that cross the municipality of Iranduba, which is traversed by the AM-352 road that connects Iranduba to the municipal seat of Novo Airão (Figure 4D). In the Low road-density region, which is the region with the highest percentage of deforested area in the Bridge scenario, the clearing penetrates areas of continuous forest.

The simulation for the Bridge scenario showed the Rio Negro SDR as having its deforested area increasing by 4601 ha between 2011 and 2030. In the Rio Negro Right Bank Environmental Protection Area (EPA), the deforested area increased by 19,496 ha. The No-bridge scenario had a lower increase in deforestation in this period, with 1634 ha cleared in the Rio Negro SDR, and 9458 ha in the Rio Negro Right Bank EPA. In the Bridge scenario there were deforestation increases of 181% and 106% in the Rio Negro SDR and the Rio Negro Right Bank EPA, respectively, as compared to the No-bridge scenario.

4. Discussion

4.1. Cumulative deforestation in simulated scenarios

A greater area was deforested in the Bridge scenario than in the No-bridge scenario in four of the five regions. These increases follow the historical trend of deforestation for the study area, which has higher rates of clearing in the calibration period for the Bridge scenario (2008 to 2010) than for the No-bridge scenario (2004 to 2006) (Supplementary Material, Table S-5). Note that the general pattern for Brazilian Amazonia as a whole, including the state of Amazonas, was for lower deforestation in the 2008-2010 period as compared to 2004-2006 (Brazil, INPE 2018), meaning that our estimates of the effect of the bridge are conservative. This is because, if one assumes the bridge had never been announced or built and that the general trends in Amazonia apply to the study area, a scenario based on calibration using 2008-2010 (i.e., the Bridge scenario but without a bridge) would project less future deforestation than would a scenario based on 2004-2006 (i.e., the No-bridge scenario)

Acceleration of urbanization with construction of the Rio Negro Bridge functioned as a catalyst simulating deforestation. In the High road-density region, even with few areas of remaining forest, deforestation spread considerably in the Bridge scenario (34% more than No-bridge scenario). The Average road-density region is still in the process of consolidating roads and the area had little variation in deforestation rate throughout the historical period (Table S-5). This resulted in little difference in deforestation between the simulated scenarios (4% more in the No-bridge scenario). The Low road-density region had deforestation expanding from its roads and also had a large percentage of forests available. This combination resulted in a large increase in deforestation (393%) in the Bridge scenario. The Very low road-density region had a 52% increase in the total area deforested in the Bridge scenario as compared to the No-bridge scenario. Finally, the River-access region had the greatest deforestation in the Bridge scenario (28%). This region is permeable by definition because river transport is part of the culture and history of the Amazon, and rivers are still an important means of transportation (Kuwahara et al. 2012; Sant’Anna 1998). What is observed in the results is that the areas that are most vulnerable to deforestation are not those immediately next to the large urban center in this case. The most vulnerable areas are those that result from the combination of ample available forest and an expanding road network (Low road-density and Very low road-density regions). The peri-urban areas feature multi-functionalities and diverse interests, and the occupation of land extends beyond the strictly urban areas. The increased accessibility of Manaus to municipalities on the right bank of the Rio Negro confirms the importance of transport infrastructure in increasing peri-urban deforestation.

The areas closest to Manaus were largely occupied prior to our study period. The area between the two rivers has extensive lowland sites with soil favorable for agriculture, supporting riverside agricultural production. Poultry raising is also an important activity in the region. With the advent of the Manaus Free Trade Zone in 1967 that created the Manaus Industrial Pole (Sá et al. 2010), the area also became important for production of building materials due to the existence of large deposits of clay. For the No-bridge scenario, simulated deforestation is the continuation of the historical rate of forest loss due to traditional economic activities (Fernandes 2013; Rodrigues et al. 2014; Sousa 2015). Some of these activities can be expected to intensify as a result of the Rio Negro Bridge. Field observations confirmed that production of fruits and vegetables is already expanding to new side roads, as are fish ponds. In the case of the Low road-density region, some secondary roads already existed, but there are now newly opened roads with deforestation foci. This can further boost future deforestation. The study area has recently been affected by major environmental impacts: at the end of 2015 (a strong El Niño year) a large area of forest burned in the "Low" and "Very low" road-density regions, and these burned areas were further deforested under the influence of the bridge.

In the No-bridge scenario, deforestation was concentrated close to previous clearing in the area closest to Manaus. In contrast, the Bridge scenario, deforestation had a pronounced expansion to more distant regions and the clearing had a diffuse pattern. This indicates that, in a context of peri-urbanization, the construction of access infrastructure can open up new deforestation frontiers, making the deforestation pattern more diffuse. The resulting fragmentation of the forest makes it even more vulnerable to degradation, including loss of biodiversity and carbon storage (Laurance et al. 2018).

4.2. Other influences on future deforestation

For the Bridge scenario, in addition to intensification of existing activities that can mean greater loss of forest cover, other activities are in the process of implementation as mentioned above. These infrastructure projects are bringing new agents and activities to the study area. Various real-estate developments, such as construction of large residential condominiums (Maciel and Lima 2013), are concentrated in the urban area of Iranduba and along the AM-070 road. But in the field, it was possible to observe that new occupations also occur in a sequence of phases in the more remote rural areas. There were lots in the demarcation phase only, others with areas that had been deforested and burned, and there were also houses under construction, some of which were accompanied by areas planted in crops.

The deforestation trend in the Bridge scenario offers a blend of the regional trend of deforestation in rural areas and a tendency to increase due to peri-urban expansion around Manaus. The simulation result for deforestation up to 2030 in the Bridge scenario is therefore likely to represent an underestimate due to the conditions that prevailed during the calibration period we used (2008-2010); deforestation in Brazilian Amazonia as a whole trended upwards from 2012 to 2017. In addition, these results do not consider the changes likely to occur with the planned reconstruction of Highway BR-319, which can be expected to increase migration to this area (Fearnside and Graça 2006). Additionally, demand for housing, food production, and other land uses will continue to increase if the trend in population growth remains as in recent years (Brazil, IBGE 2015). The Rio Negro Bridge allows production in the affected area to be restructured with the support of government development policy; this is similar to previous development projects in Amazonia, which have generally not improved the living conditions of residents where the projects are installed (Sousa 2011).

4.3. New frontiers of deforestation versus conservation units

In the Bridge scenario deforestation became more diffuse. In addition to occurring in the area near Manaus and the municipal seats, it also spread along new side roads branching off the AM-352 road, an area that had previously been little deforested. This area has a variety of ecotourism attractions, such as river beaches and streamside bathing places. The large number of tourists from Manaus has stimulated interest in acquiring land both for leisure and for commuter housing in an area that offers some urban amenities (Maciel and Lima 2013; Rodrigues et al. 2014).

Land access in these protected areas is restricted to the AM-070 and AM-352 roads and their associated secondary roads. Much of the area under protection can only be reached by river or by seaplane. Despite this continued lack of accessibility for much of the area under protection, the Rio Negro Bridge can be an inducer of increased environmental degradation. The Rio Negro SDR was created at the beginning of the construction period of the Rio Negro Bridge as part of government plans to mitigate the environmental impacts of the bridge by creating protected areas (Brazil, AGU 2009; FAS 2010). Simulated deforestation in the Bridge scenario was 181 and 106% more than in the No-bridge scenario for Rio Negro SDR and the Rio Negro Right Bank EPA. Even in areas with conservation units and little previous deforestation, one can expect that there will be an increase of deforestation with the construction of infrastructure in the region. The existence of natural amenities in the city’s surroundings can attract human occupation.

The conservation units in the study area lacked management plans entirely during our calibration periods. The Rio Negro RDS, which was created in 2008, only had its management plan approved in 2017. New deforestation has continued to appear in the Rio Negro SDR in the years since this conservation unit was created. Without a management plan, a conservation unit has no way to guide actions in accord with its objectives and founding principles, and the different uses of environmental resources cannot be reconciled with biodiversity conservation. Nevertheless, in addition to the need for suitable management plans for the conservation units, measures need to be taken to monitor and supervise activities in these areas.

4.4. Considerations of unregulated occupation and their implications for deforestation, and modeling in the context of peri-urban expansion

In the Bridge scenario there is also a new process of deforestation due to peri-urbanization. The largest simulated percentage increases in deforested areas occurred in the regions with “Low” and “Very low” road density. These are the regions that offer the largest areas of available forest and their road networks have expanded in recent years, thus making them more susceptible to new occupations. Added to this attraction is the push from increasing land prices in the city of Manaus, including land for industry (Sá et al. 2010). Increased interest in peri-urban areas often results from growing competition for available areas and the consequent high cost of construction in city centers (Shi et al. 2012). Real-estate speculation is one of the most prominent economic activities on the right bank of the Rio Negro and has environmental and social implications leading to more clearing along roads and around the urban areas of Iranduba and Manacapuru (Sousa 2015). In many of the side roads we visited there were signboards, fences, stakes and other markings for subdividing land into residential lots. At some locations houses were being built and electricity, satellite dishes and telephone lines were already present. However, in many houses we could not find anyone. Other properties only had either a caretaker or hired workers preparing land or building houses. Many of these houses are used only for recreation on the weekends. There are many properties along the smaller roads with "for sale" signs, including roads that still have no electricity. Proximity of a major metropolis to a rural area can speed deforestation, since large owners often live in urban centers, meaning that the financial resources for the deforestation are also close by (Fearnside 2008). The prior existence of residences in a given area is often an important driver to promote development of new peri-urban dwellings (e.g., Liu and Robinson 2016); this increases the probability of land-cover change in these newly opened areas.

Lack and insecurity of housing are major factors in environmental degradation in Manaus and other large cities in Brazil’s northern region (COHRE 2006). Intense and disorderly occupation resulting from invasions by the low-income population has removed primary forest in the urban area of Manaus (GEO-Cidades 2002). With the bridge this dynamic can be expected to spread to the other side of the river, where there is no effective environmental control policy. Land tenure is still fragile in rural portions of the study area (Rodrigues et al. 2014; Sousa 2015), and legal measures for environmental protection cannot be taken until the status of the land is defined (Sparovek et al. 2012). Other problems associated with these occupations include pollution of soils, rivers and ground water, loss of biodiversity and reduction of the carbon stock (e.g., Aguilar and Santos 2011). If effective measures for spatial planning are not taken, it is likely that the number of illegal occupations will increase on the right bank of the Rio Negro.

Although Brazilian Amazonia had a deforestation rate of 4571 km^2/year in 2012, the lowest since 1988 when official monitoring began, the rate has trended upward since then, reaching 6947 km^2/year in 2017 (Brazil, INPE 2018). Increased deforestation can be expected due to the basic drivers of the process having either grown or remained unchanged, including the profitability of agriculture, road-construction plans and continuing increase in population and investment in the region (Fearnside 2015). Large cities in Brazil’s northern region are undergoing disorderly urbanization and they lack housing and urban planning. The Brazilian government has been impervious to the appeals and recommendations of the scientific community, and a series of recent harmful policies threatens ecosystem services and biodiversity in Brazil (Azevedo-Santos et al. 2017; Fearnside 2016, 2018). Government institutions involved in the conservation of this area should pay special attention to changes in land cover in the area along the AM-352 road and in the western portion of the municipality of Iranduba. These are areas that have great potential for deforestation.

Despite inherent uncertainty in simulation with a model based on cellular automata and data from a geographic information system (GIS) (Yeh and Li 2006), models based on cellular automata have better performance in simulating urban sprawl than do models using mathematical equations (Supplementary Material, Appendix 7) (Santé et al. 2010; Yeh and Li 2006). Future models can be improved by inclusion of deforestation agents and economic variables. The reality of land-cover change is complex, and, like all models, the AGROECO model used here is a simplified representation of this reality. Nevertheless, the model provides information needed for decision making on territorial organization and environmental conservation.

5. Conclusions

Deforestation has been expanding in the peri-urban area on the right bank of the Rio Negro during and after construction of a bridge that connected this area to the city of Manaus in 2011. Simulation of scenarios with and without the bridge indicate the potential impact of the bridge on deforestation through 2030. In the Bridge scenario, edge-expansion peri-urbanization increased and cumulative deforestation was much greater than in the No-bridge scenario, with outlying expansion of peri-urbanization having occurred by 2030. This demonstrates the possible impact of infrastructure that improves the connection of large urban centers with their peri-urban surroundings. Such infrastructure projects can not only abruptly increase deforestation, they can also disperse this activity to new deforestation frontiers, thus making the forests even more vulnerable. In simulated scenarios there was a substantial increase of deforested area with construction of the bridge, even inside conservation units. It is necessary to develop a management plan and effective policies for environmental control in areas exposed to increased deforestation pressure.

The simulations show that construction of the Rio Negro Bridge can change the rate and location of deforestation on the right bank of the river. Of the five regions we considered in our study area, the region with the highest percentage increase in deforestation provoked by the bridge was not the closest to Manaus, but rather was the “Low road-density” region that had the greatest area of preserved forest and that was in the process of expansion of secondary roads. By 2030, the area assessed by the AM-352 road in the municipality of Iranduba could to be heavily deforested. However, in absolute terms the "River access" region was the most deforested in both scenarios, highlighting the importance of rivers for mobility in the region. The urbanization process in the municipalities of Iranduba, Manacapuru and Novo Airão is free to continue, thereby strengthening the process of deforestation. Unless adequate planning and monitoring of new occupations and enforcement of environmental restrictions are implemented, the improved access that the bridge provides from the city of Manaus can be expected to further accelerate deforestation. Urban areas are increasingly important as drivers of land-use change throughout the world, including the Amazon region, and peri-urban frontiers such as the one created by the Rio Negro bridge may be expected to play an increasing role in tropical deforestation.

Acknowledgments

Funding was provided by Conselho Nacional do Desenvolvimento Científico e Tecnológico (CNPq: Proc 304020/2010-9; 311103/2015-4; 573810/2008-7), Fundação de Amparo à Pesquisa do Estado do Amazonas (FAPEAM: Proc 708565), Programa de Capacitação Institucional, Ministério de Ciência, Tecnologia e Comunicação (MCTIC Proc: 313157/2015-4), and Instituto Nacional de Pesquisas da Amazônia (INPA: 15,125.PRJ). This article is a contribution of the Brazilian Research Network on Global Climate Change, FINEP/ Rede CLIMA Grant Number 01.13.0353-00.

Conflicts of interest

The authors declare that they have no conflicts of interest and that the study complies with all laws in Brazil.

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Figure legends

Figure 1. Map of the Manaus Metropolitan Region (MMR), which was created in 2007 encompassing the city of Manaus and several municipalities in Brazil's state of Amazonas.

Figure 2. Map of deforestation by 2010 based on PRODES data from Brazil, INPE (2018) (A). And regionalization of the study area based on road density: A- High density; B- Average density; C- Low density, D-Very low density and E- River access (B).

Figure 3. Cumulative area (ha) of deforestation from 2011 to 2030 simulated for each scenario for the study area as a whole and for each road-density region on the right bank of the Rio Negro under direct influence of the bridge.

Figure 4. Simulated map of land-cover dynamics by 2030 for the No-bridge scenario (A) and for the area nearest to Manaus (B). Simulated map of land-cover dynamics by 2030 for the Bridge scenario (C) and for the area along Highway AM-352 (D).

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Table 1. Spatial variables used as input data in the AGROECO model.

Category	Variables	Source
Static variables	Soil	Radam Brasil Project (Brazil, IBGE 2007)
	Vegetation	Radam Brasil Project (Brazil, SIPAM 2007)
	Altitude and slope	Shuttle Radar Topography Mission (Brazil, EMBRAPA 2005)
	Hydrographic	Derived from PRODES (Brazil, INPE 2018)
	Conservation units	Brazil, MMA 2015
	Municipal seats	Derived from Brazil, IBGE 2008
	Settlements	Brazil, INCRA 2014; see also Yanai et al. 2017
	Indigenous land	Brazil, FUNAI 2016; see also Nogueira et al. 2018
	Road network	Updated from data provided by Remote Sensing Center of the Federal University of Minas Gerais
Dynamic variables	Distance to the nearest road	Calculation performed by software Dinamica-EGO (Soares-Filho et al. 2009)
	Distance to the nearest previously deforested	Calculation performed by software Dinamica-EGO (Soares-Filho et al. 2009)

Table 2. Periods used in each scenario for the stages of the deforestation simulation.

Stage	No-bridge scenario	Bridge scenario	Justification
Calibration	2004-2006	2008-2010	Bridge construction began in December 2007, and this year was therefore adopted as the reference year for separating the deforestation data for the two scenarios. Because three years was used for the reference period for the No-bridge scenario, a reference period of the same length was also used for the Bridge scenario.
Simulation	2007-2030	2011-2030	The simulation in each scenario begins in the year following the last year of the calibration period. Therefore, the simulation starts in 2007 for the No-bridge scenario and in 2011 for the Bridge scenario. The periods used for calibration are short, and the time horizons of the simulations were therefore limited to 2030 in order to reduce uncertainties. Since the bridge is recent and the dynamics of land-cover change are still adjusting in the affected area, it is reasonable to do a simulation for only 23 years. This is shorter than the time horizons of other studies of Amazonian deforestation, which have simulated deforestation over intervals of more than 40 years (e.g., Fearnside et al. 2009; Soares-Filho et al. 2006; Yanai et al. 2012).
Comparative results	2011-2030	2011-2030	The year 2011 is the first year with simulated deforestation in both scenarios. This year was considered as the base year in order to facilitate the comparison of results.
Regionalization based on the density of roads	2004-2014	2004-2014	The year 2004 is the first year used in calibration. Regionalization was done until 2014 to have a 10-year historical period of road dynamics in the study area.

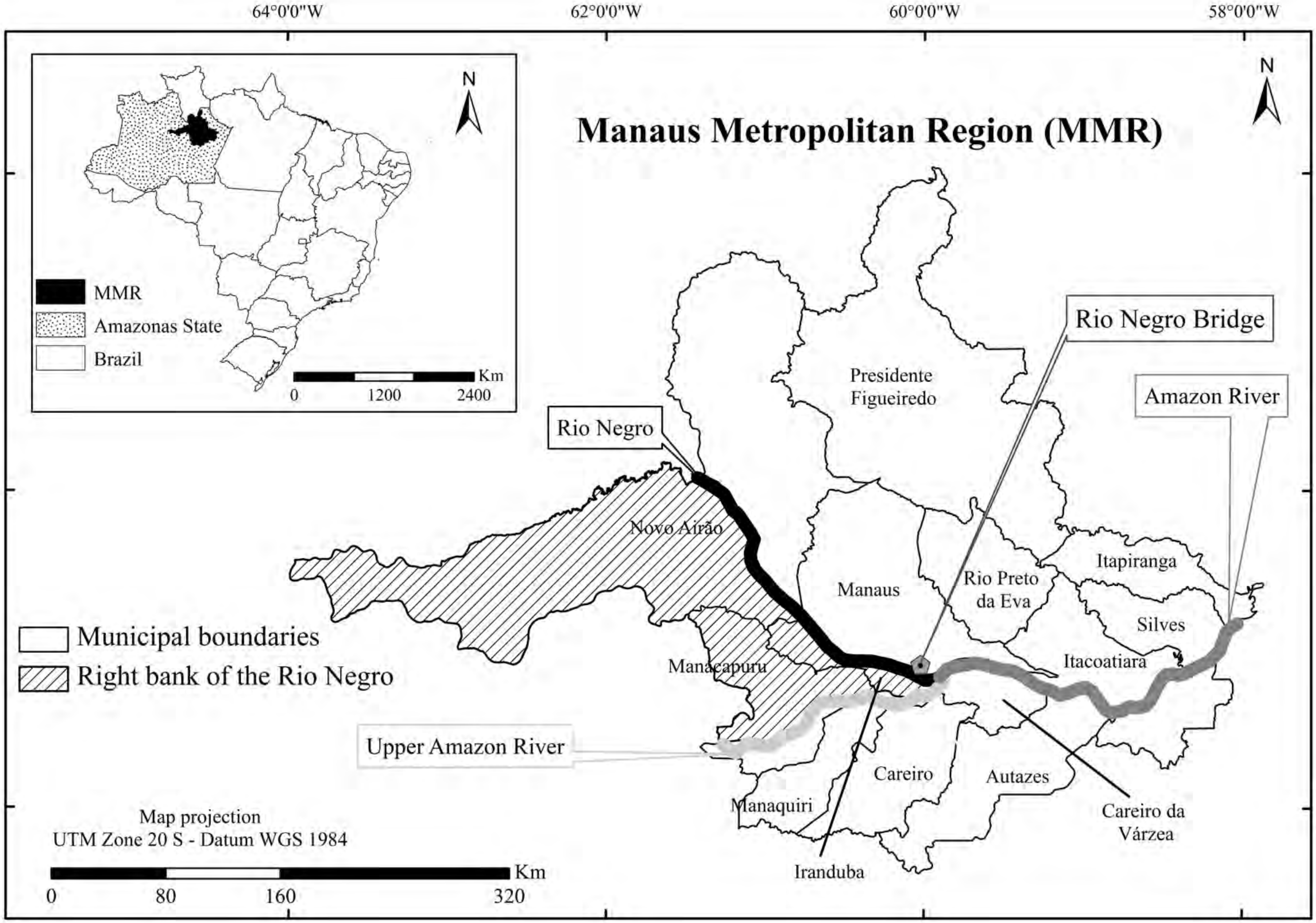
Table 3. Deforestation and forest area (ha) inside and outside of the “agrarian forest surface” (AFS) in the No-bridge and Bridge scenarios by region.

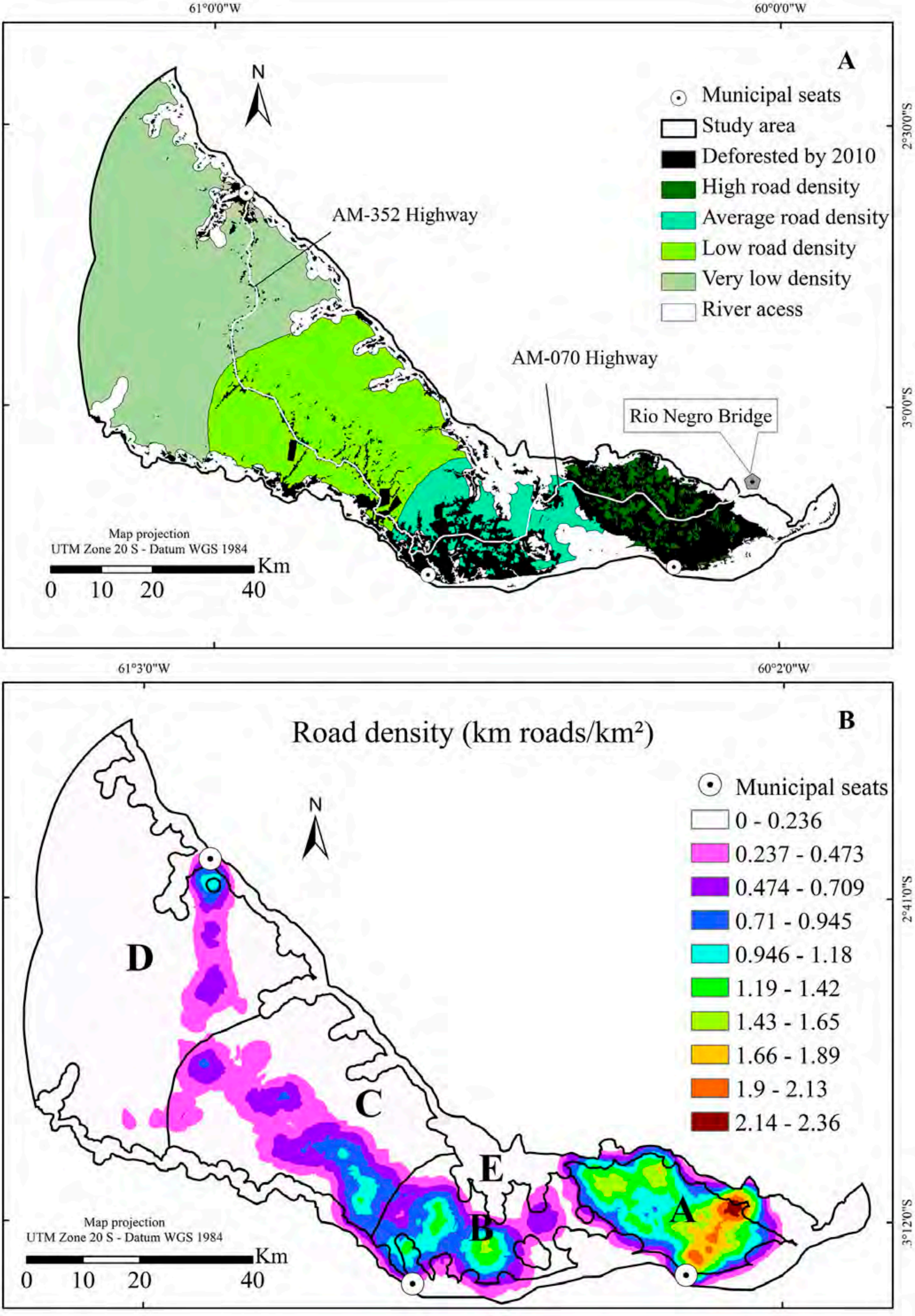
Area (ha) of No-bridge scenario

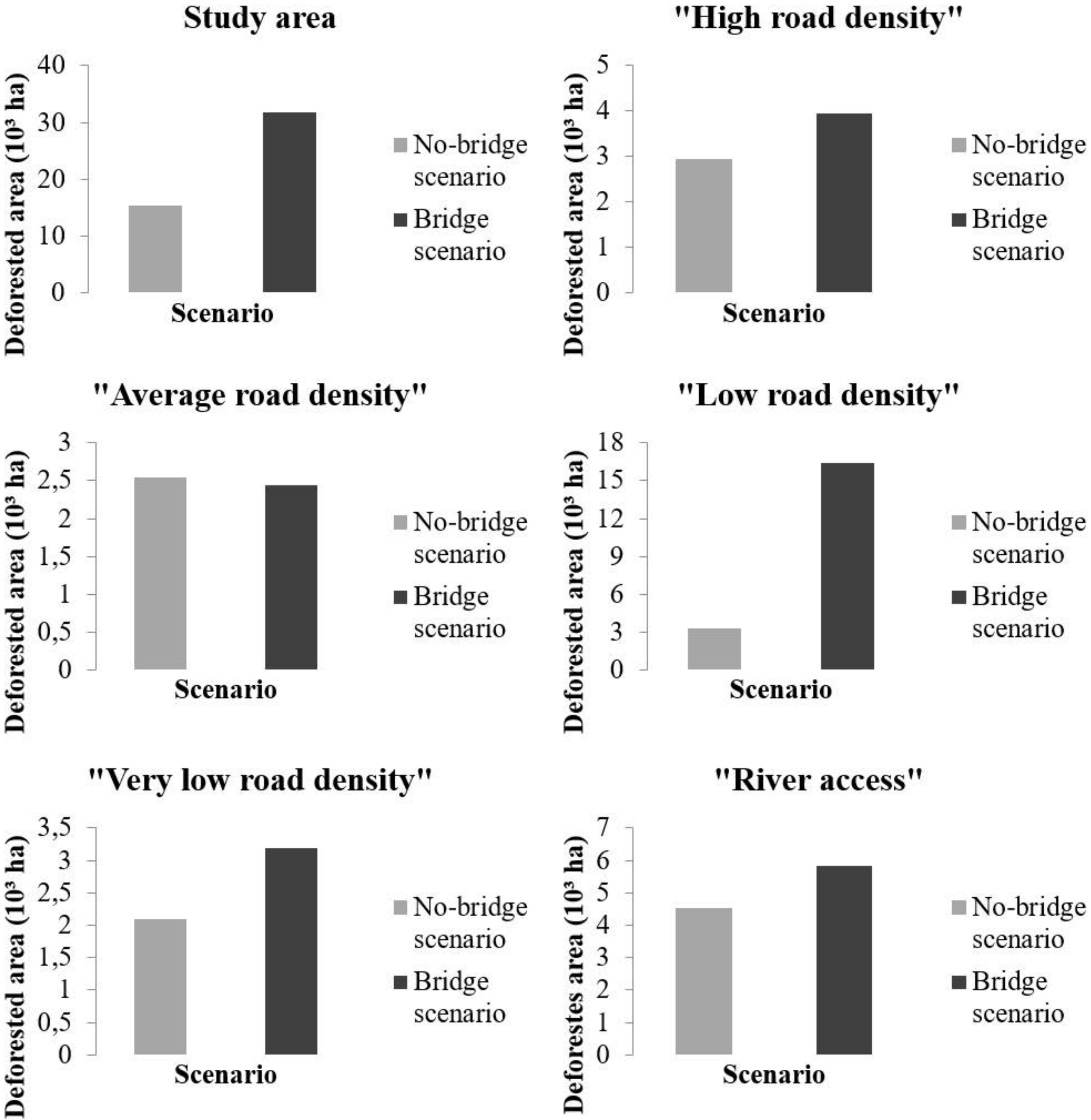
	Region	High road density		Average road density		Low road density		Very low road density		River access	
Year	Category	Deforested	Forest	Deforested	Forest	Deforested	Forest	Deforested	Forest	Deforested	Forest
2004	AFS	30,032.6	11,875.6	17,305.9	24,036.4	7,037.2	50,760.0	1,815.8	23,346.7	18,152.6	11,999.5
	Outside AFS	4.3	38.8	406.0	6,168.9	434.8	62,693.2	167.0	167,195.5	10,205.2	46,830.2
2006	AFS	30,432.9	11,475.3	17,539.2	23,803.2	7,263.3	50,533.9	1,945.4	23,217.1	18,228.9	11,934.7
	Outside AFS	4.3	38.8	407.5	6,167.5	444.9	62,683.2	213.1	167,149.4	10,671.8	46,363.6

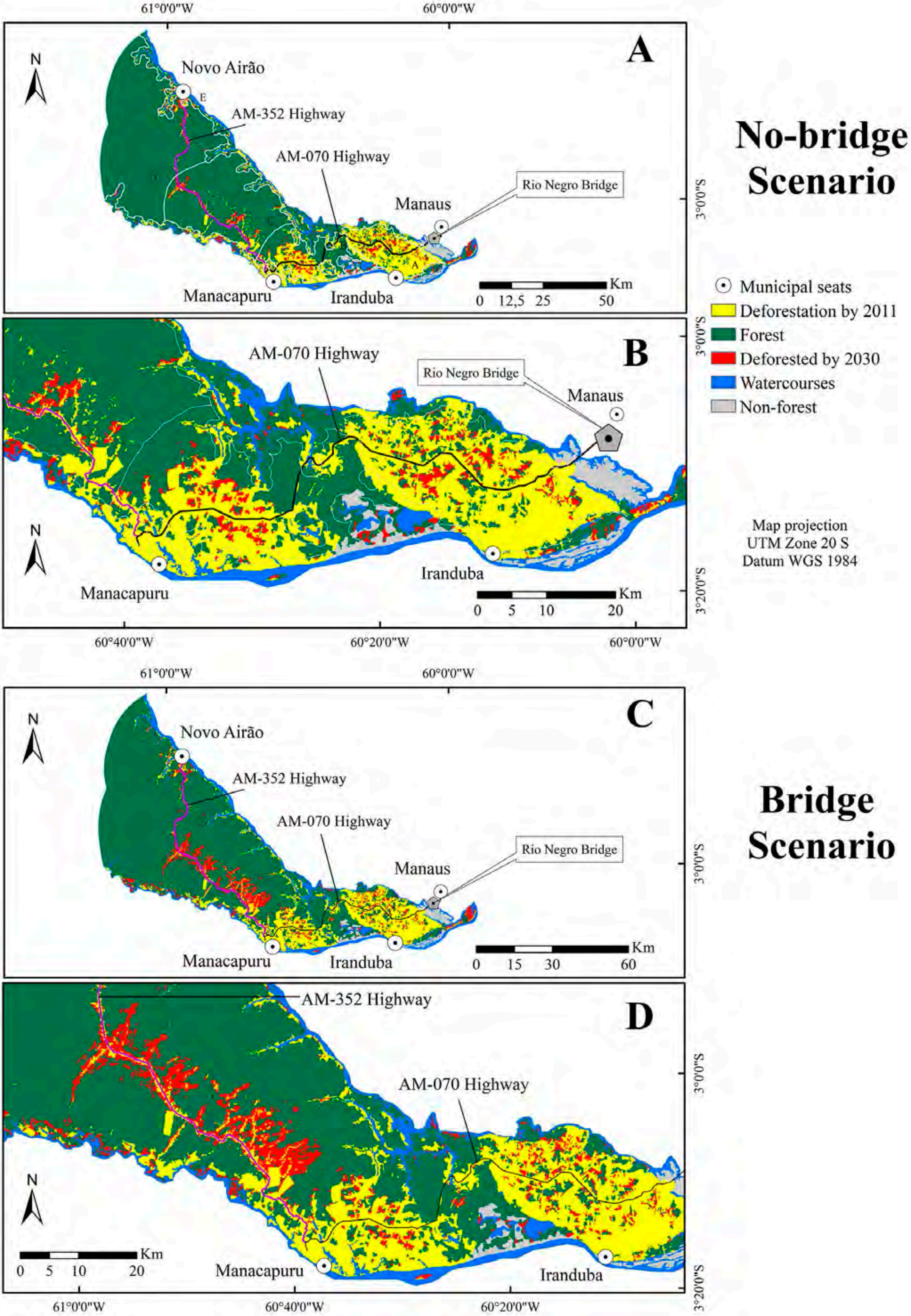
Area (ha) of Bridge scenario

	Region	High road density		Average road density		Low road density		Very low road density		River access	
Year	Category	Deforested	Forest	Deforested	Forest	Deforested	Forest	Deforested	Forest	Deforested	Forest
2008	AFS	30,869.2	11,039	17,601.1	23,741.2	7,463.5	50,333.7	2,043.3	23,119.2	18,228.9	11,923.2
	Outside AFS	4.3	38.8	407.5	6,167.5	444.9	62,683.2	213.1	167,149.4	10,730.8	46,304.6
2010	AFS	31,419.3	10,488.9	17,831.5	23,510.8	8,442.7	49,354.5	2,217.6	22,944.9	18,388.8	11,763.3
	Outside AFS	4.3	38.8	416.1	6158.8	472.3	62,655.8	292.3	167,070.2	11,208.9	45,826.5


Manaus Metropolitan Region (MMR)
64°0'0"W
62°0'0"W
60°0'0"W
58°0'0"W
0°0'0"
2°0'0"S
4°0'0"S
N
N
■ MMR
▨ Amazonas State
☐ Brazil
Km
0
1200
2400
Rio Negro Bridge
Amazon River
Rio Negro
Presidente Figueiredo
Novo Airão
Manaus
Rio Preto da Eva
Itapiranga
Silves
Itacoatiara
Manacapuru
Upper Amazon River
Careiro
Autazes
Manaquiri
Careiro da Várzea
Iranduba
☐ Municipal boundaries
▨ Right bank of the Rio Negro
Map projection
UTM Zone 20 S - Datum WGS 1984
Km
0
80
160
320


61°0'0"W
60°0'0"W
A
Municipal seats
Study area
Deforested by 2010
High road density
Average road density
Low road density
Very low density
River acess
AM-352 Highway
AM-070 Highway
Rio Negro Bridge
2°30'0"S
3°0'0"S
N
Map projection
UTM Zone 20 S - Datum WGS 1984
Km
0
10
20
40
61°3'0"W
60°2'0"W
B
Road density (km roads/km²)
Municipal seats
0 - 0.236
0.237 - 0.473
0.474 - 0.709
0.71 - 0.945
0.946 - 1.18
1.19 - 1.42
1.43 - 1.65
1.66 - 1.89
1.9 - 2.13
2.14 - 2.36
2°41'0"S
3°12'0"S
N
D
C
E
B
A
Map projection
UTM Zone 20 S - Datum WGS 1984
Km
0
10
20
40


Study area
Deforested area (10³ ha)
40
30
20
10
0
Scenario
No-bridge scenario
Bridge scenario
"High road density"
Deforested area (10³ ha)
5
4
3
2
1
0
Scenario
No-bridge scenario
Bridge scenario
"Average road density"
Deforested area (10³ ha)
3
2,5
2
1,5
1
0,5
0
Scenario
No-bridge scenario
Bridge scenario
"Low road density"
Deforested area (10³ ha)
18
15
12
9
6
3
0
Scenario
No-bridge scenario
Bridge scenario
"Very low road density"
Deforested area (10³ ha)
3,5
3
2,5
2
1,5
1
0,5
0
Scenario
No-bridge scenario
Bridge scenario
"River access"
Deforestes area (10³ ha)
7
6
5
4
3
2
1
0
Scenario
No-bridge scenario
Bridge scenario


No-bridge Scenario
Bridge Scenario
A
B
C
D
Novo Airão
Manaus
Manacapuru
Iranduba
AM-352 Highway
AM-070 Highway
Rio Negro Bridge
E
61°0'0"W
60°0'0"W
60°40'0"W
60°20'0"W
3°0'0"S
3°20'0"S
N
Km
0 12,5 25 50
0 5 10 20
0 15 30 60
Municipal seats
Deforestation by 2011
Forest
Deforested by 2030
Watercourses
Non-forest
Map projection
UTM Zone 20 S
Datum WGS 1984

Supplementary Online Material

Deforestation dynamics on an Amazonian peri-urban frontier: Simulating the influence of the Rio Negro Bridge in Manaus, Brazil

Camila Julia Pacheco Ramos[1] (camilajramos@gmail.com)
Paulo Maurício Lima de Alencastro Graça[2,3] (pmlag@inpa.gov.br)
Philip Martin Fearnside[2, 3,] * (pmfearn@inpa.gov.br)

[1]Programa de Pós Graduação em Ecologia, Instituto Nacional de Pesquisas da Amazônia(INPA), Av. André Araújo, 2936, Manaus, Amazonas, 69067-375, Brazil
[2]Coordenação de Dinâmica Ambiental, Instituto Nacional de Pesquisas da Amazônia (INPA), Av. André Araújo, 2936, Manaus, Amazonas, 69067-375, Brazil
[3]Brazilian Research Network on Climate Change (RedeClima), Environmental Services subnetwork, INPA, Av. André Araújo, 2936, Manaus, Amazonas, 69067-375, Brazil
*corresponding author
pmfearn@inpa.gov.br
INPA, Av. André Araújo, 2936, Manaus, Amazonas, 69067-375, Brazil
Telephone: +55 92 3643-1822 Fax: +55 92 3642-3028

Appendix 1. Field observations

Observations were made over nine days from July to September 2014. Points of interest were first identified on an image map for 2014 made from Landsat-8 data from the Operational Land Imager (OLI). The sampled points were those where deforestation occurred in recent years according to the classification by PRODES. These points were chosen based on road access after updating the road map for the region. The points of interest were then sampled in the field. Fieldwork included informal conversations with local residents to understand the nature of land-cover change in the area.

The social profile of the property owners in the study area is very diverse, including small farmers, engineers, lawyers, doctors, merchants and low-income population from the periphery of Manaus.

Appendix 2. Maps of attractiveness and friction for road construction

The attractiveness map was prepared by weighting based on criteria that favor road construction and hence deforestation. Attractiveness is calculated based on numerical maps where areas close to forests and areas with dense networks of roads have the highest values, and flooded areas and areas with less roads have the lowest values. The same method was done for the calculation of the friction map. The areas with the highest values are protected areas, as well as areas near rivers (which are difficult to access). These variables provide a cost surface for the opening of new roads.

Appendix 3. Periods used to calibrate the scenarios

The periods used for calibration, despite being short, are representative of the scenarios to be simulated. The bridge began to be built in December 2007, thus this year was adopted as the reference year for separating the deforestation data collection for the two scenarios. Because three years was used for the reference period for the "No-bridge" scenario, the same three-year range was also used for the reference period for the “Bridge” scenario. Other simulations of Amazonian deforestation have also used short periods to calibrate the scenarios, such as the studies of Barni et al. (2015), who used the period from 2004 to 2007, and Soares-Filho et al. (2002), who used two periods: 1986-1991 and 1991-1994.

Appendix 4. Map Correlation Analysis

The only necessary condition for applying the weights-of-evidence method is independence of the variables used in the model (Bonham-Carter et al. 1989). Dinamica-EGO therefore has a function that performs a series of spatial-independence tests. These tests analyze spatial dependence between pairs of input variables (Soares-Filho et al. 2009). Both the Cramer test and Joint Information Uncertainty yield indices with values ranging from 0 to 1, such that values close to 1 indicate greater spatial correlation between pairs of variables. Variables with indices from the independence tests with values above 0.5 should be discarded (Agterberg and Bonham-Carter 2005; Macedo et al. 2013; Yanai et al. 2012). For this study, conditional independence of variables was obeyed.

Appendix 5. Updating the rates of transition

The validation for the total area of cumulative deforestation for both scenarios was around 7%. A variety of percentage errors was found when we evaluated the error for each region. For the No-bridge scenario, the error ranged from -34.8% to 0% for the "Low" and "High" road-density regions, respectively. In the Bridge scenario the error ranged from - 20.9% to 0.2% for the "Low" road-density and "River access" regions, respectively. Because of this variation, it was decided to make a correction of the rate by region. The area that showed an error in the simulation of cumulative deforestation was the "Low" road-density region, which had newly opened roads. The calculation of the annual net rate of deforestation takes into account the concept of “agrarian forest surface” (Barni et al. 2015; Fearnside et al. 2009; Yanai et al. 2012). An area that has newly opened roads may not have consolidated deforestation around the roads, which reduces the calculated annual net rate of deforestation to be used in the AGROECO model. After updating the transition rates, validation of the simulated cumulative deforestation was satisfactory. In the "Low" road-density region, which previously had the highest percentage errors, these errors decreased to -1.2% and -1.9% in the No-bridge and Bridge scenarios, respectively.

Appendix 6. History of deforestation for each road-density region

The deforestation rate in the study area fluctuated widely within the period analyzed (Figure S-10). In the early years it remained relatively constant at about 800 ha/year. After a decline up to 2008, the rate increased in 2009 (the highest for the entire period), followed by another decline in 2010. This trend is reflected in the different road-density regions, but there are some peculiarities. The High road-density region had the largest fluctuations, with 2004 and 2007 showing the highest rates of deforestation: 377 and 332 ha/year, respectively. In the Average road-density region the first and the last few years showed the highest deforestation rates. In 2006 the deforestation rate was calculated at 126 ha/year, and in 2009 at 132 ha/year. In the Low road-density region there was constancy up to 2008, with deforestation rate remaining around 130 ha/year. Beginning in 2009 the rate increased to 650 ha/year. In the Very low road-density region the deforestation rates varied, but there was a downward trend in the early years followed by an increase in 2009. In the River-access region the highest rates were at the beginning and at the end of the period of analysis, with 335 ha/year in 2005 and 372 ha/year in 2009.

Appendix 7. Uncertainties and improvements in modeling

Uncertainties stem from errors in source data in the GIS databases, technical limitations and the complex nature of the processes the model is intended to simulate (Yeh and Li 2006). Nevertheless, cellular-automata models feature simplicity, flexibility and the ability to integrate spatial and temporal dimensions of the processes they represent (Santé et al. 2010; Yeh and Li 2006). A limitation in this study is the extent to which the first validation reflects the total amount of deforestation for each scenario. In the second validation this error was attenuated (Supplementary Material Appendix 4).

Future models can be improved by inclusion of additional factors. More explicit modeling is needed of the different deforestation agents such as farmers, loggers, people from the city of Manaus who buy land for weekend retreats, and new residents who commute to work in Manaus. Other models could explicitly include economic variables such as increasing per-capita income and an increase in the financial contribution of the state government in the area after construction of the bridge. The reality of land-cover change is complex, and the AGROECO model used here is a simplified representation of this reality. Nevertheless, it provides information needed for decision making on territorial organization and environmental conservation.

Table S-1. Values adopted for building the maps of attractiveness and friction for road construction. For the No-bridge scenario the data used were for 2006, and for the Bridge scenario the data were for 2010. SDR =Sustainable Development Reserve; NP = National Park; EPA = Environmental Protection Area.

Attractiveness		
Land cover		
Forest	10	
Deforestation	4	
Watercourse	1	
Non-forest	1	
Roads		
Inside buffer of 5 Km	15	
Outside buffer of 5 Km	1	
Regions of Study Area		
	No-bridge scenario	Bridge scenario
High road density	2	2
Average road density	2	2
Low road density	4	6
Very low road density	2	2
River access	1	1
Friction		
Land cover		
Forest	1	
Deforestation	1	
Watercourse	40	
Non-forest	40	
Conservation units		
Non-protected areas	1	
Rio Negro SDR	1	
Anavilhanas NP	10	
Rio Negro Right Bank EPA	1	
Indigenous lands		
Non-indigenous lands	1	
Fortaleza do Patuá	10	
Jatuarana	10	

Table S-2. Initial net rate values for average annual deforestation in the historical period used to calibrate each scenario inside and outside of the "agrarian forest surface" (AFS).

	Region									
	High road density		Average road density		Low road density		Very low road density		River access	
Scenario/ Years	**AFS**	**Outside AFS**	**AFS**	**Outside AFS**	**AFS**	**Outside AFS**	**AFS**	**Outside AFS**	**AFS**	**Outside AFS**
No bridge/ 2004 - 2006	0.01714	0	0.00487	0.00011	0.00223	0.00008	0.00278	0.00013	0.0027	0.005
Bridge/ 2008 - 2010	0.02555	0	0.00487	0.0007	0.00982	0.00021	0.00378	0.00023	0.00674	0.00518

Table S-3. Validation of the amount of land-cover change by region in the simulated maps as compared to the observed maps (NB = No-bridge; B= Bridge).

Initial validation

Region	High road density		Average road density		Low road density		Very low road density		River access	
Scenario	NB	B	NB	B	NB	B	NB	B	NB	B
% Deforestation error	0	0.78	-12.26	-1.8	-34.75	-20.88	-9.01	-0.56	0.27	-0.22

Validation after update

Region	High road density		Average road density		Low road density		Very low road density		River access	
Scenario	NB	B	NB	B	NB	B	NB	B	NB	B
% Deforestation error	0	0.26	1.84	0	-1.21	-1.85	0	2.84	0	0.22

Table S-4. Updating of the net rate values for average annual deforestation in the historical period used to calibrate each scenario inside and outside of the "agrarian forest surface" (AFS).

	Region									
	High road density		Average road density		Low road density		Very low road density		River access	
Scenario/ Years	AFS	Outside AFS	AFS	Outside AFS	AFS	Outside AFS	AFS	Outside AFS	AFS	Outside AFS
No bridge/ 2004 - 2006	0.01714	0	0.00555	0.00012	0.00341	0.00012	0.00305	0.00014	0.00269	0.00498
Bridge/ 2008 - 2010	0.02535	0	0.00495	0.00071	0.01241	0.00026	0.0038	0.00023	0.00675	0.00519

Table S-5. History of deforestation rate by road-density region for each calibration period according to data from Brazil, INPE (2017).

	Study area	**High road density**	**Average road density**	**Low road density**	**Very Low road density**	**River access**
Deforestation rate 2004/2006	789.12	200.16	117.36	118.08	87.84	265.68
Deforestation rate 2008/2010	1343.52	275.04	119.52	503.28	126.72	318.96

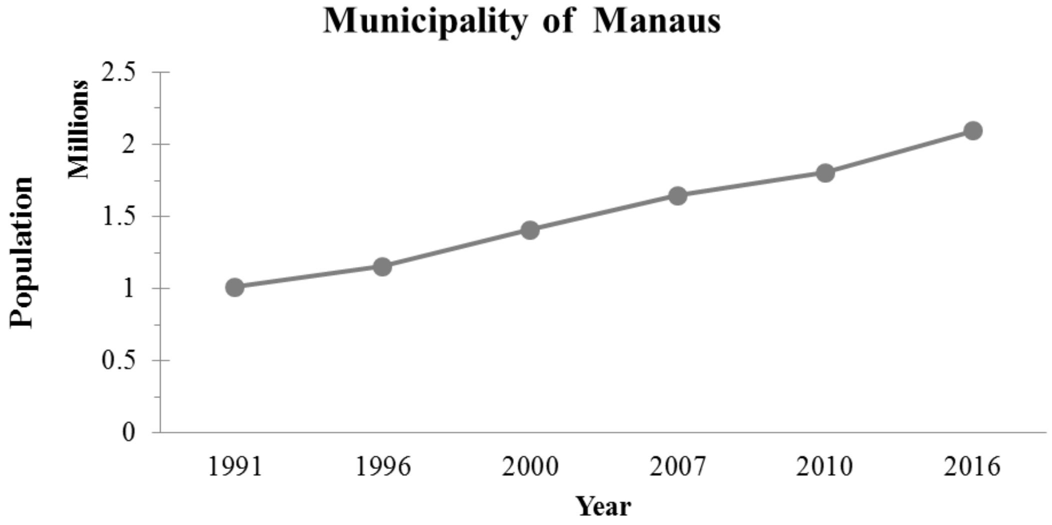


Figure S-1. Population growth data for the municipality of Manaus. Data source: Brazil, IBGE (2017): Demographic Census 1991, Population count 1996, Demographic Census 2000, Population count 2007, Demographic Census 2010 and Estimated Population 2016.

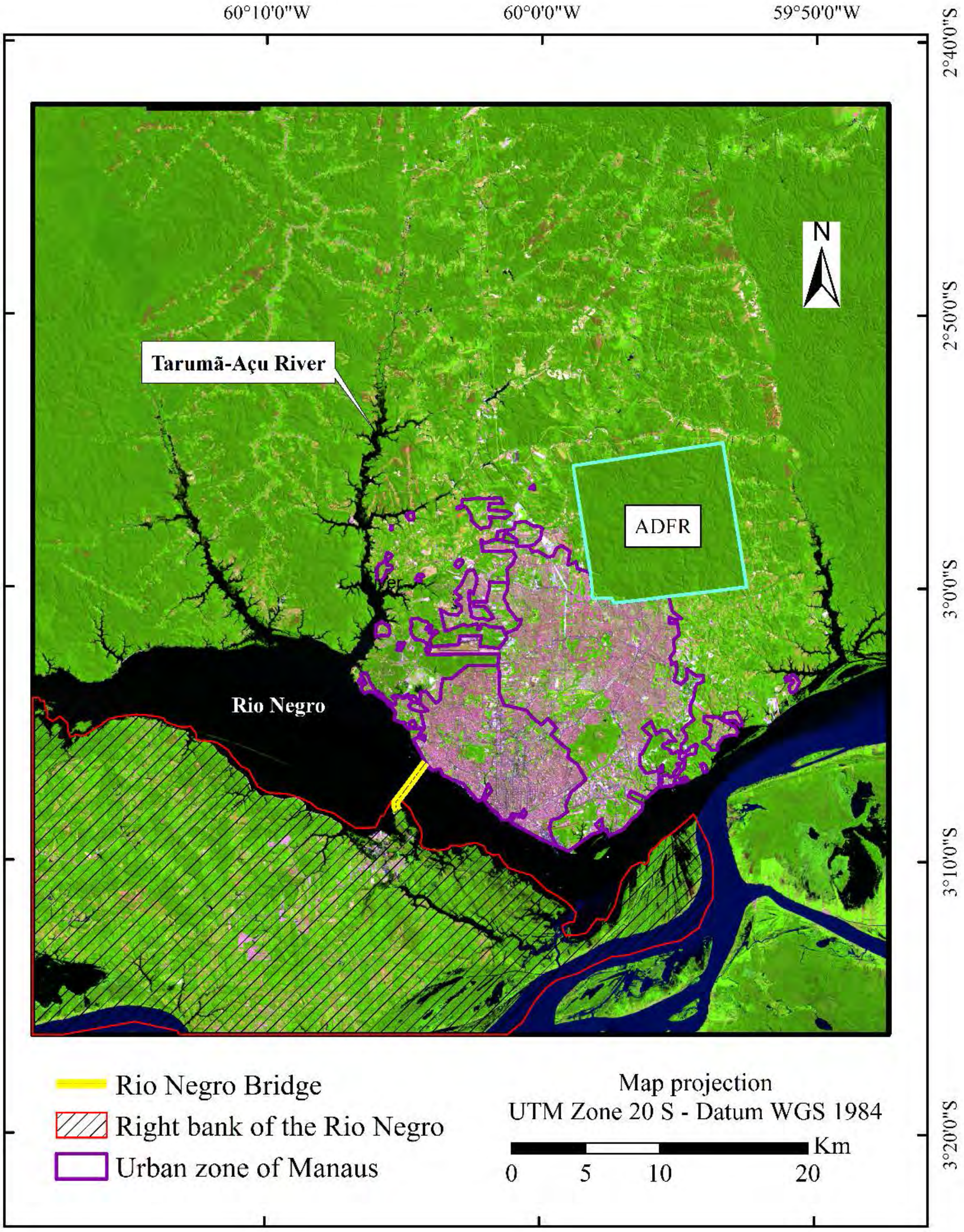


Figure S-2. Map of the connection created between the city of Manaus and the study area. ADFR = Adolpho Ducke Forest Reserve.

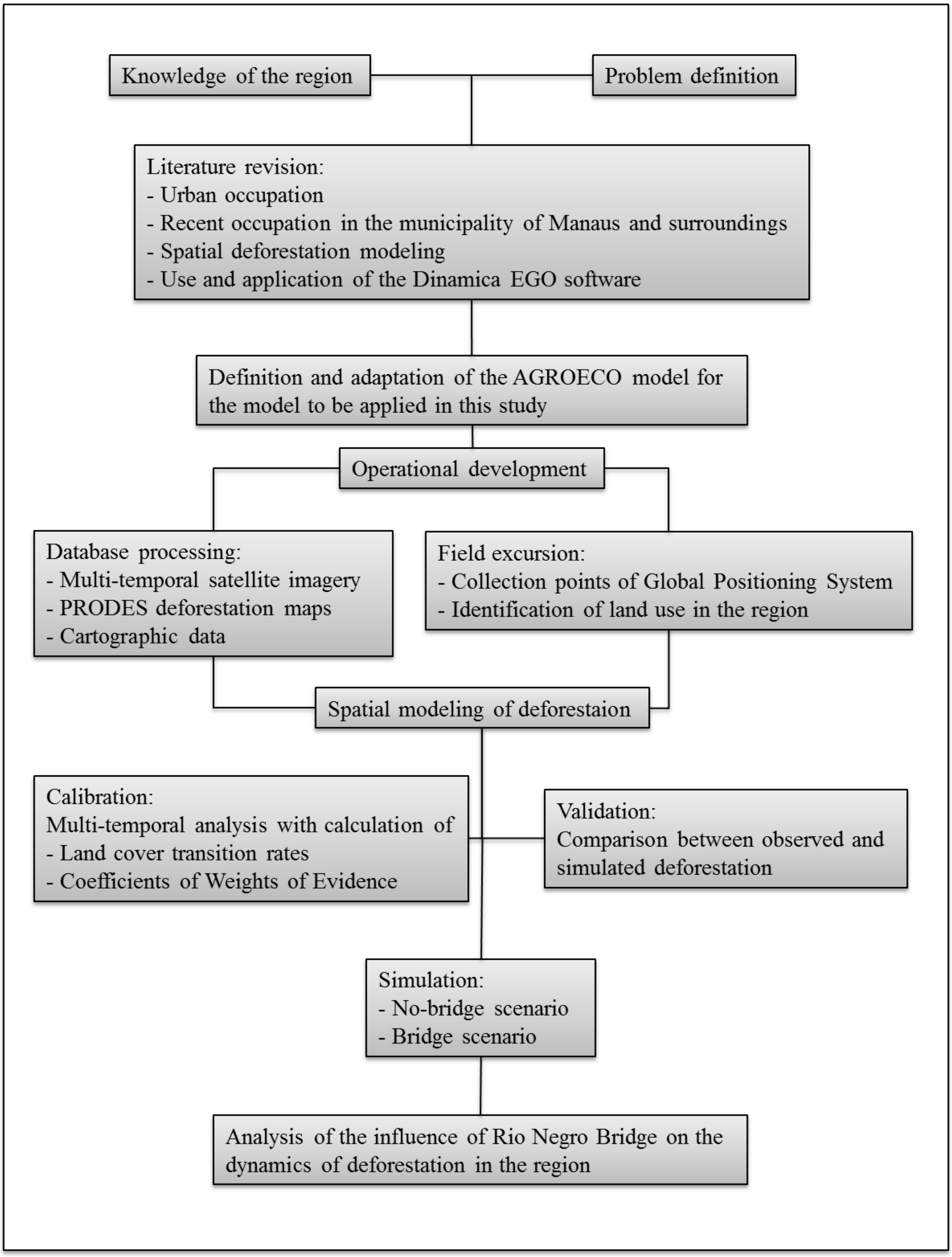


Figure S-3. Flowchart of the conceptual steps in the present study.

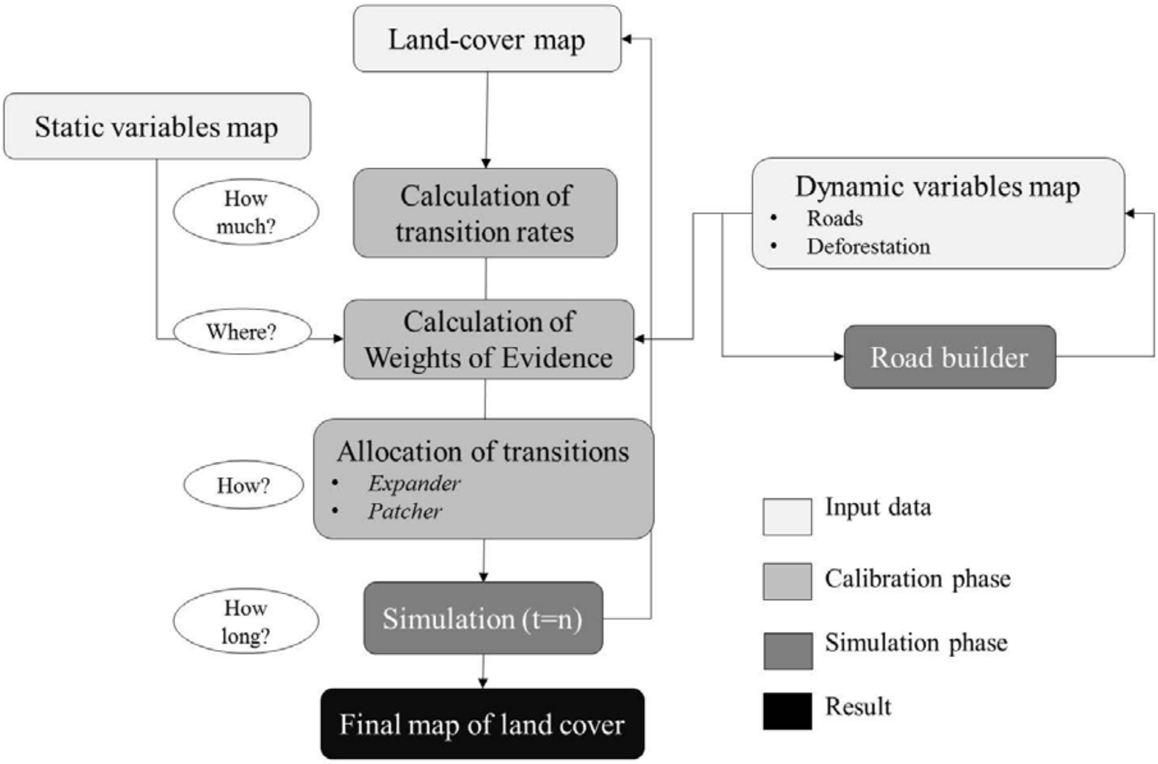


Figure S-4. Flowchart of the conceptual model of land-use and cover change using Dinamica-EGO (Adapted from Vitel 2009).

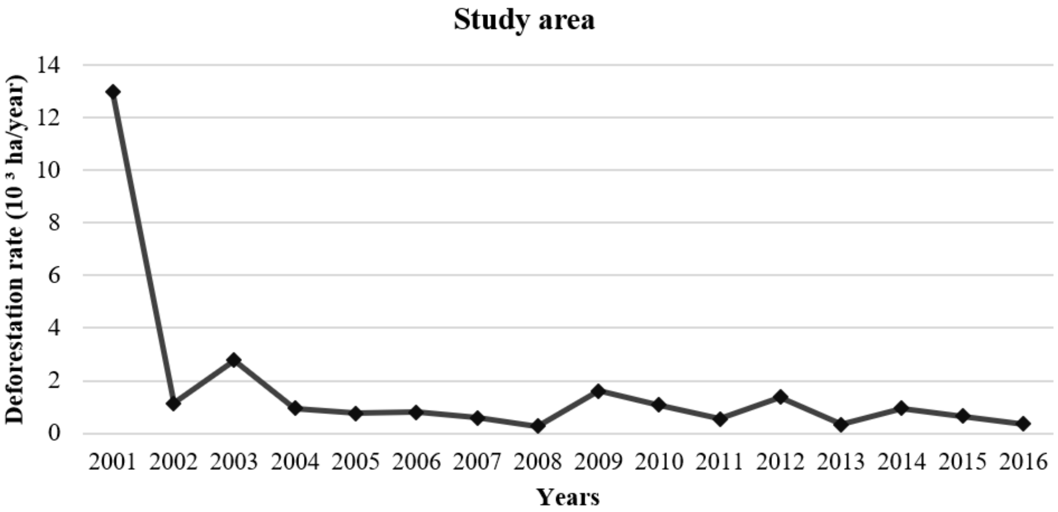
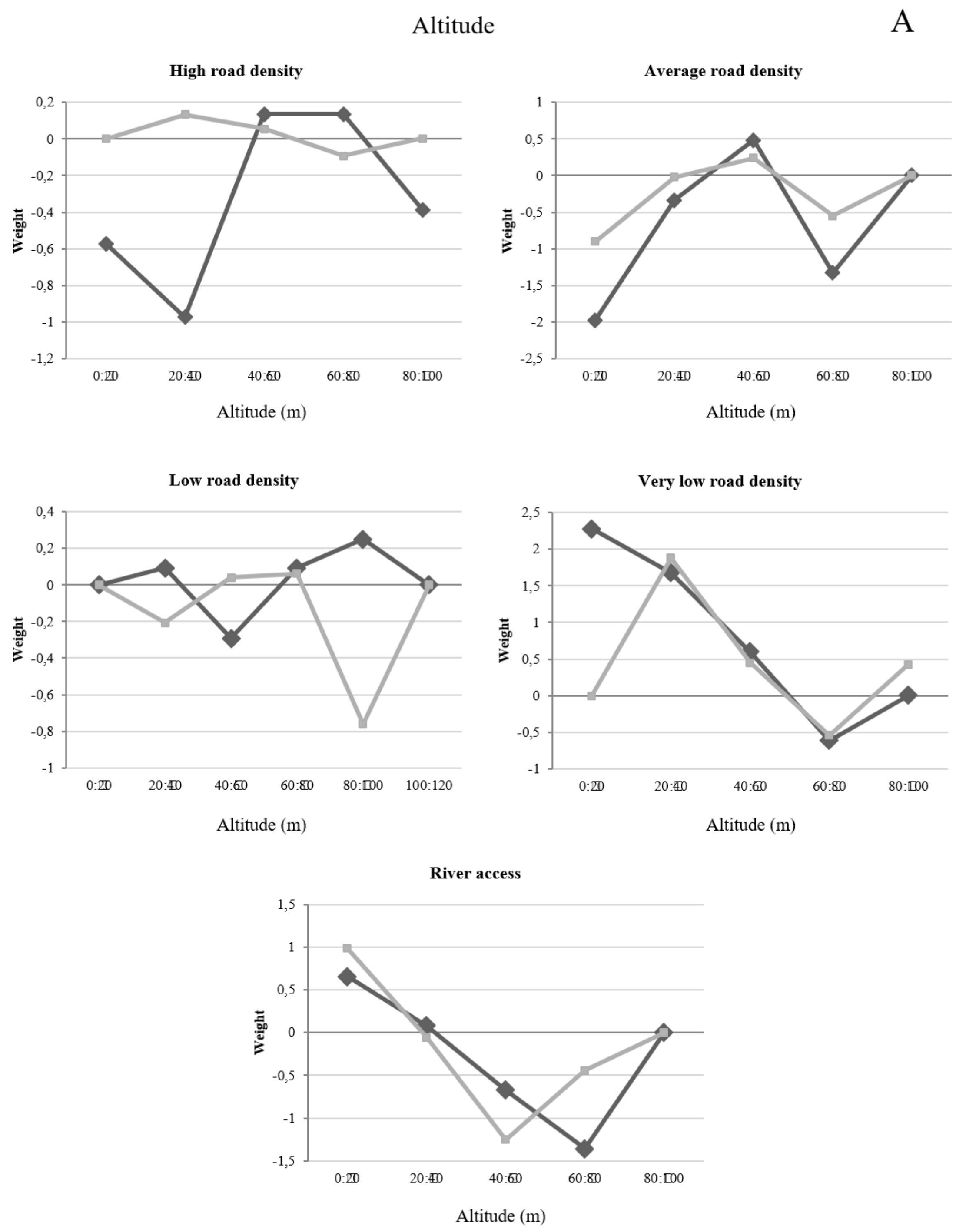
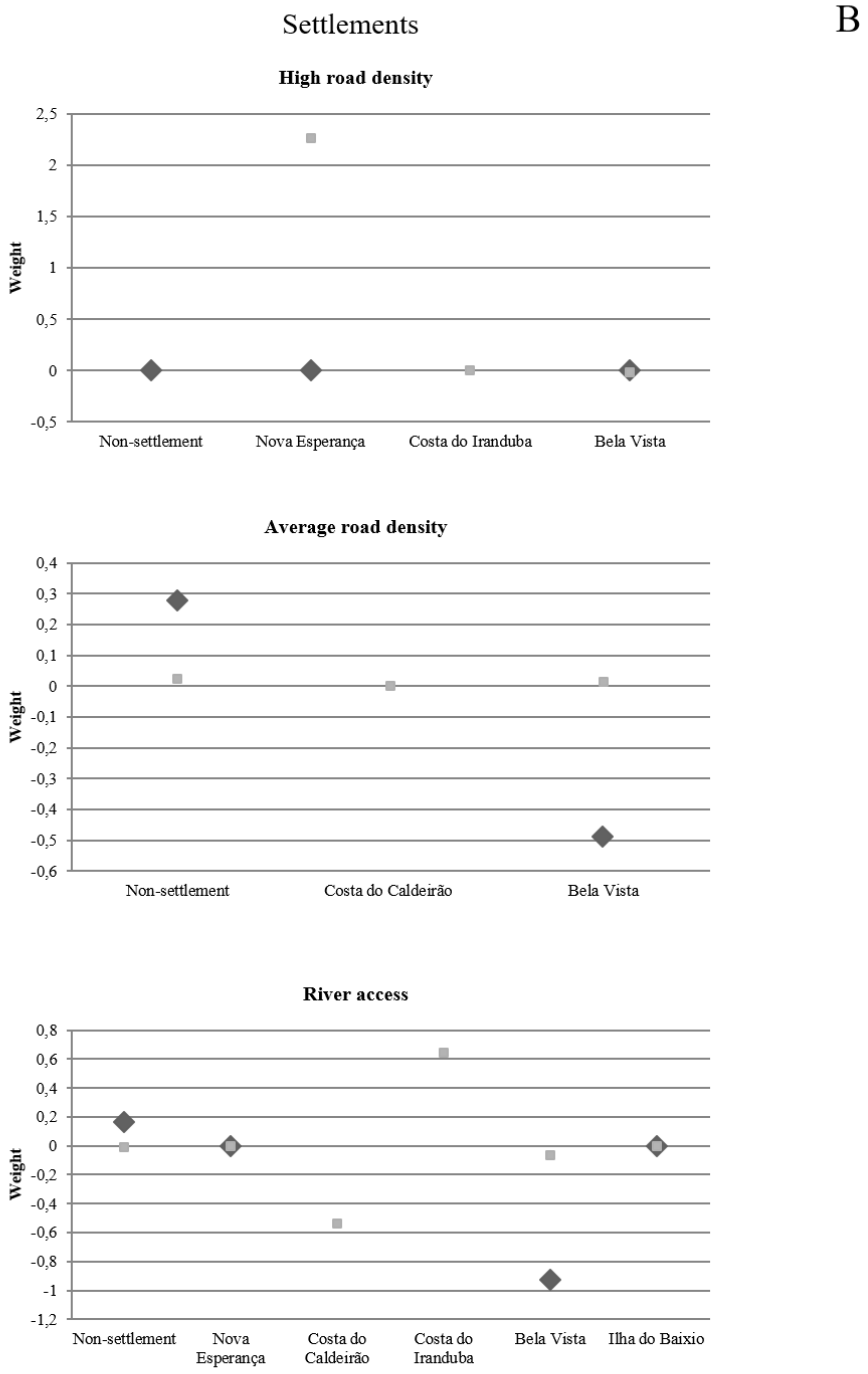


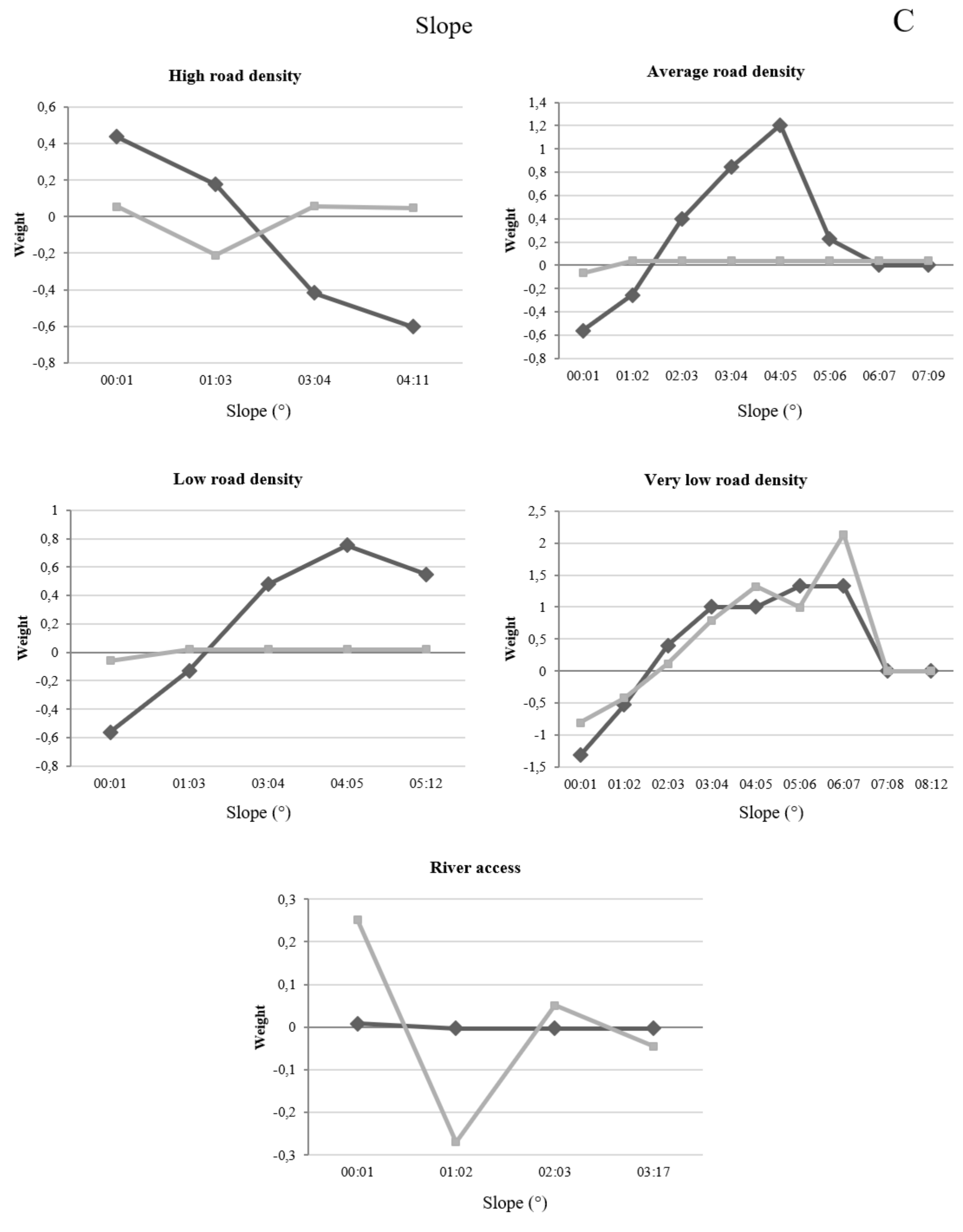
Figure S-5. History of deforestation rate to study area according to data from Brazil, INPE (2017).



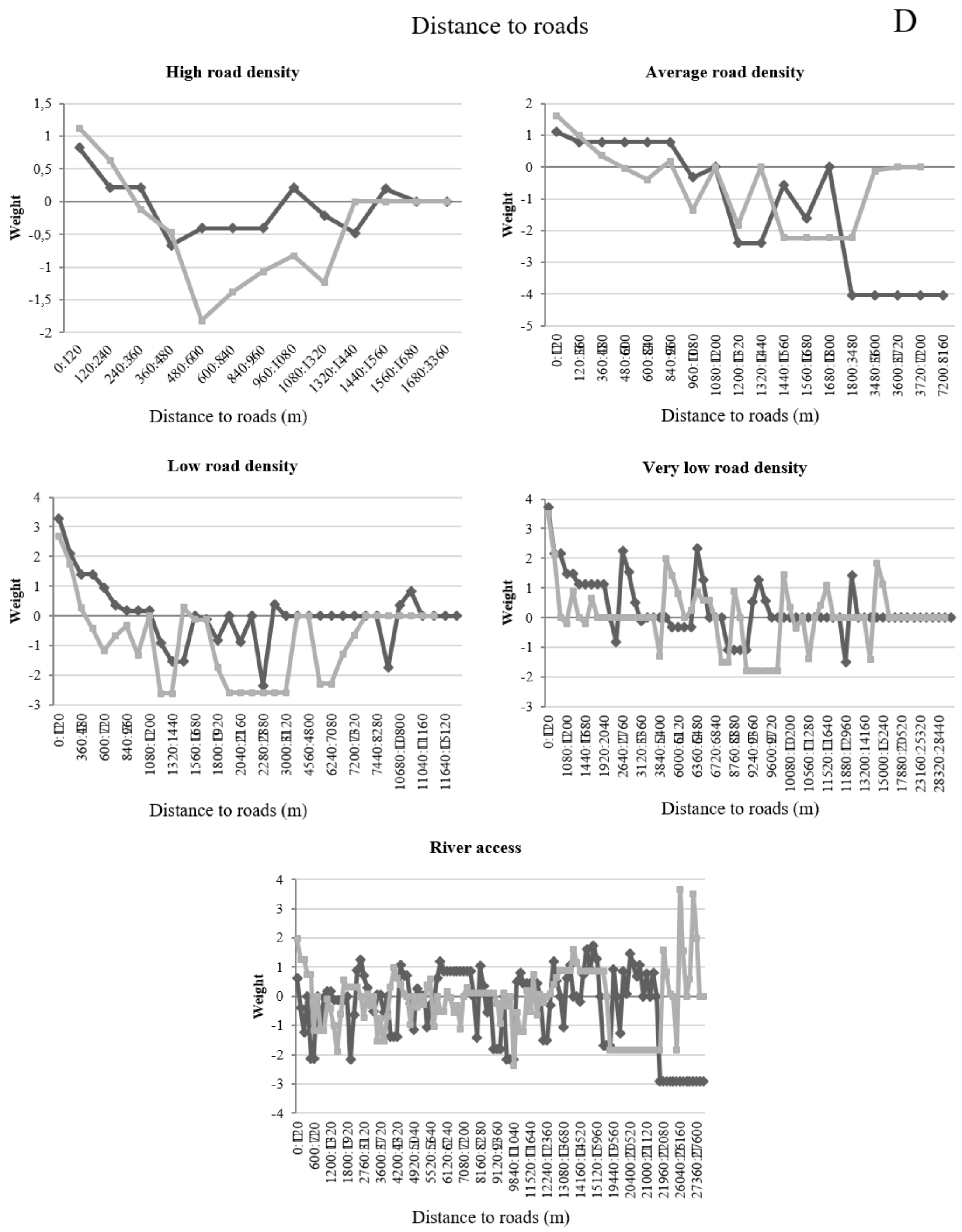
Legend: Dark symbols = No-bridge scenario; light symbols = Bridge scenario.



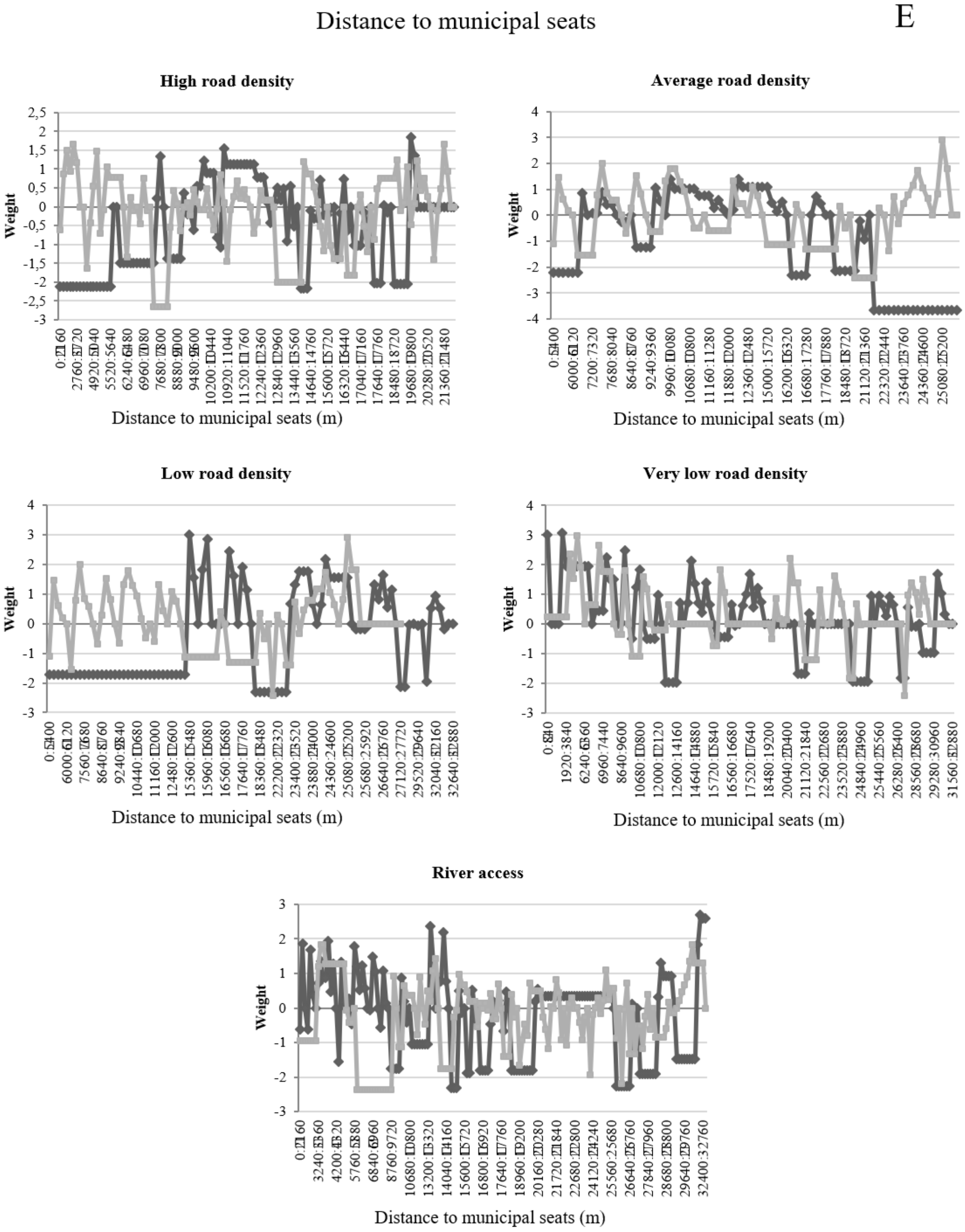
Legend: Dark symbols = No-bridge scenario; light symbols = Bridge scenario.



Legend: Dark symbols = No-bridge scenario; light symbols = Bridge scenario.



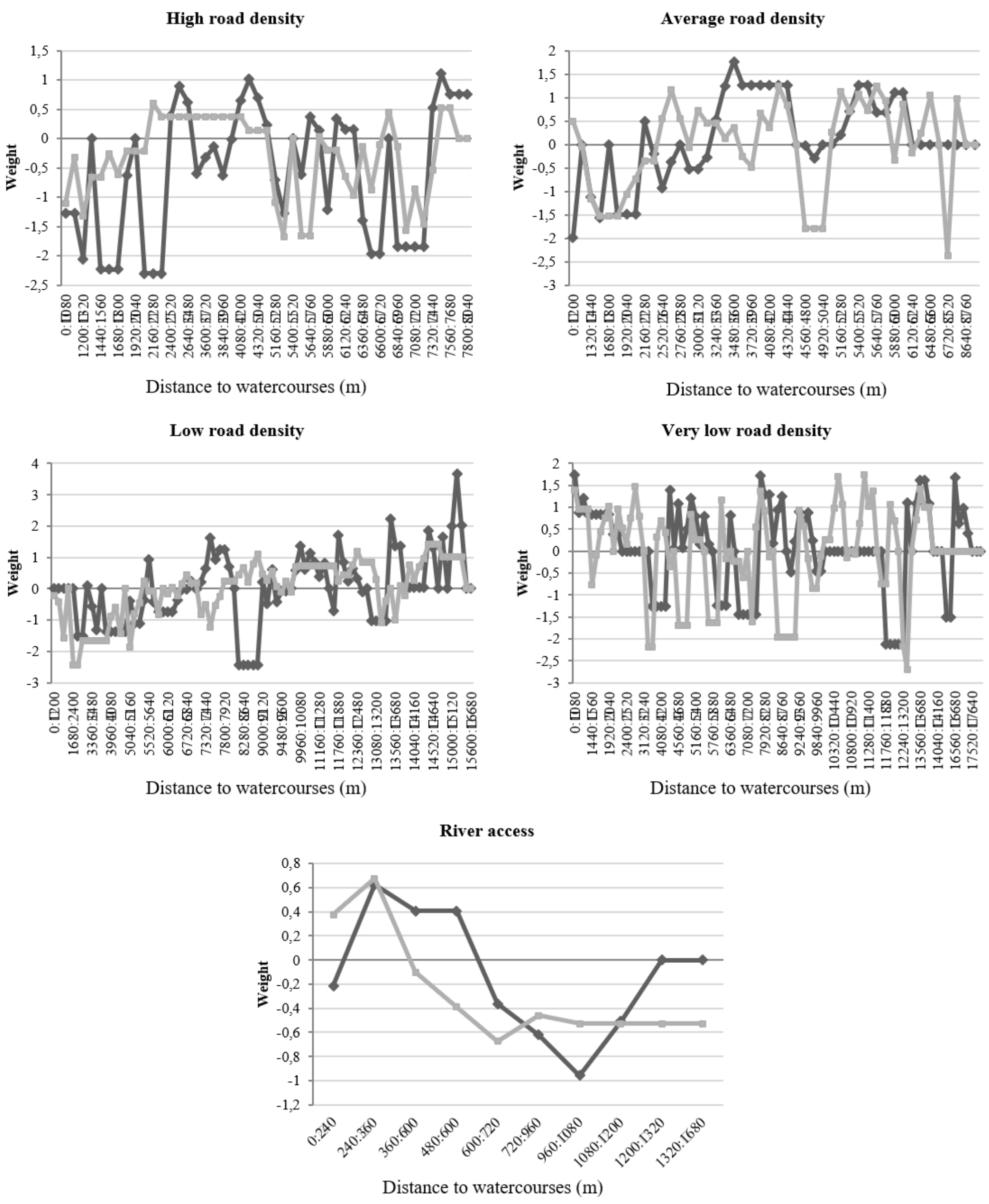
Legend: Dark symbols = No-bridge scenario; light symbols = Bridge scenario.



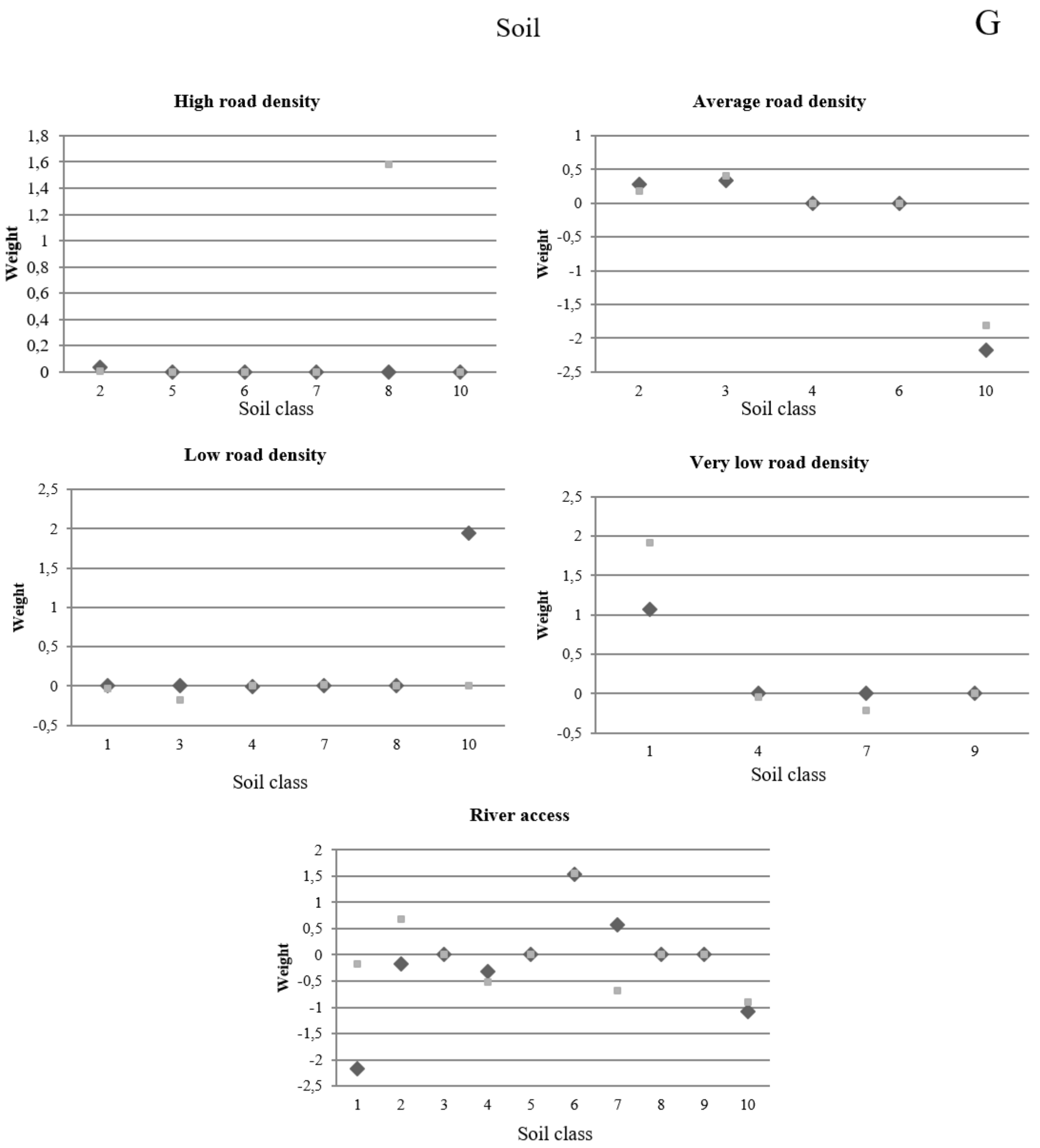
Legend: Dark symbols = No-bridge scenario; light symbols = Bridge scenario.

Distance to watercourses

F



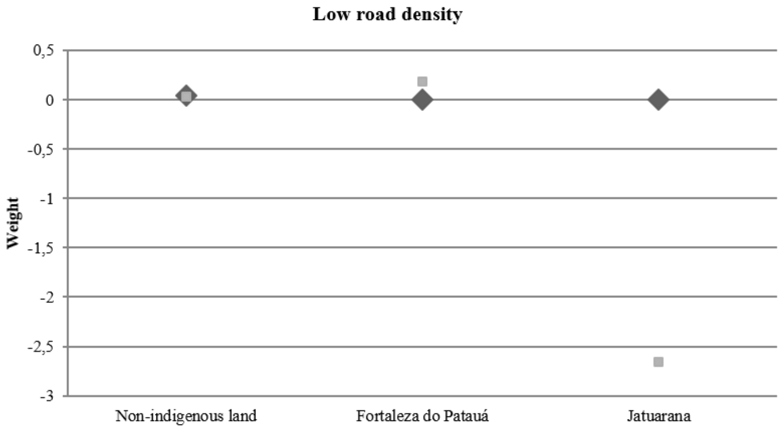
Legend: Dark symbols = No-bridge scenario; light symbols = Bridge scenario.

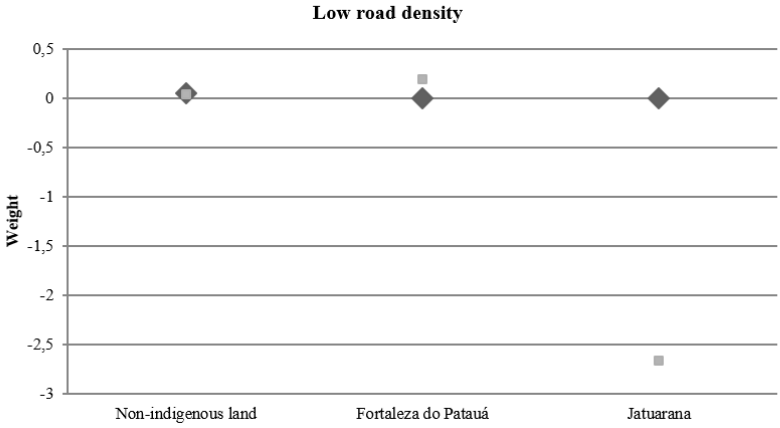


Legend: 1 = *Podzólico vermelho amarelo* (*Argissolo*) [Ultisol; Acrisol], 2 = *Latossolo amarelo* (*Latossolo*) [Oxisol; Ferralsol], 3 = *Petroplíntico* (*Latossolo*) [Oxisol; Ferralsol], 4 = *Podzol hidromórfico* (*Latossolo*) [Spodosol; Podzol], 5 = *Plintossolo* (*Plintossolo*) [Entisol; Lithosol], 6 = *Aluvial* (*Neossolo*) [Histosol; Histosol], 7 = *Gleissolo* (*Gleissolo*) [Inceptisols; Gleysols], 8 = *Gleissolo húmico* (*Neossolo*) [Inceptisols; Gleysols], 9 = *Areia quartzosa hidromórfica* (*Gleissolo*) [Inceptisols; Gleysols], 10 = *Latossolo vermelho-amarelo* (*Plintossolo*) [Entisol; Lithosol]. * For soil types, the corresponding name in the new Brazilian nomenclature (Brazil, IBGE 1992) is given in parentheses beside each RadamBrasil soil class (Brazil, Projeto RadamBrasil 1972-1983; do Prado 2001), while the US Soil Taxonomy and FAO/UNESCO units are given in brackets (Beinroth 1975). Dark symbols = No-bridge scenario; light symbols = Bridge scenario.

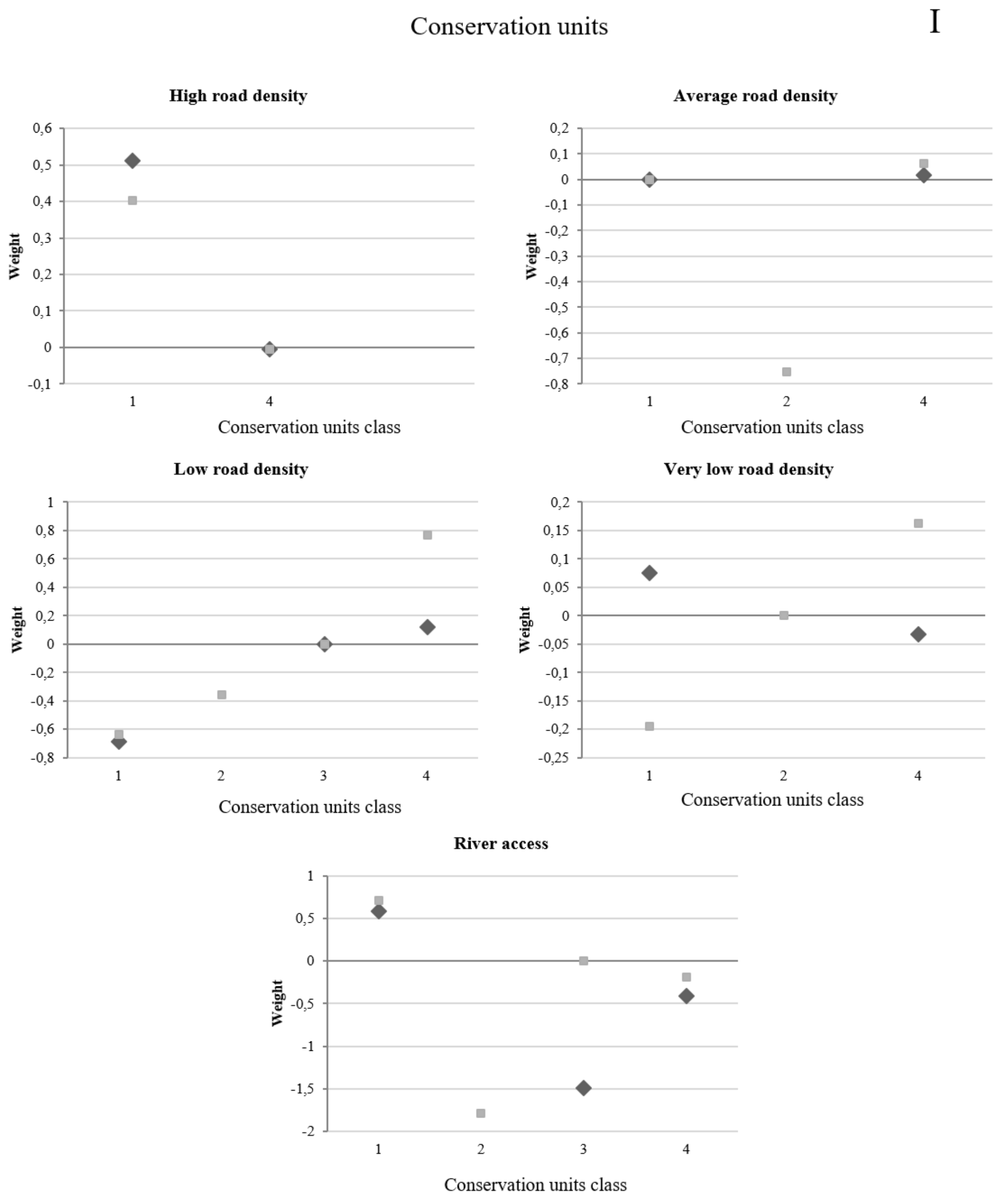
Indigenous land

H

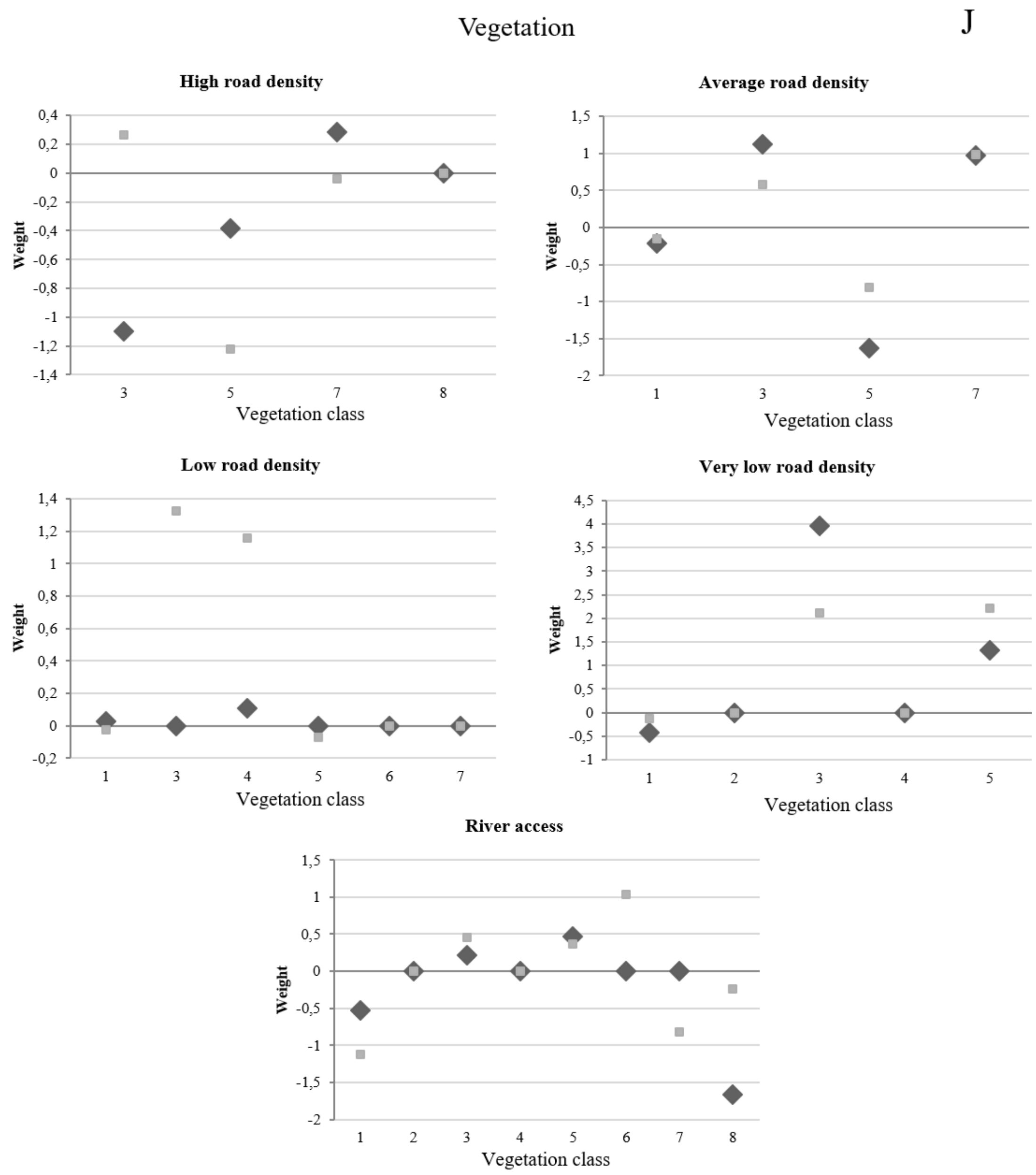




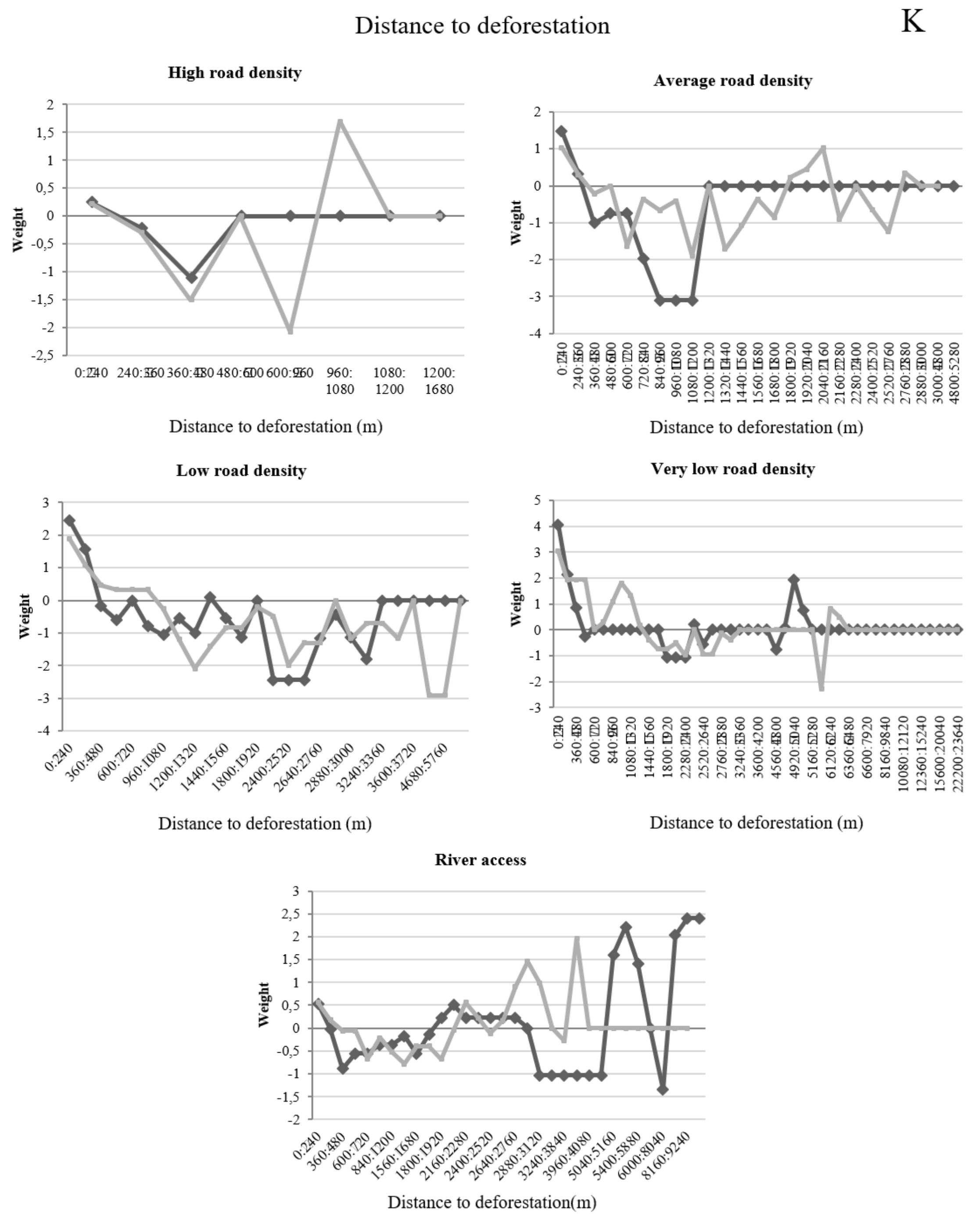
Legend: Dark symbols = No-bridge scenario; light symbols = Bridge scenario.



Legend: 1 = Non-conservation units, 2 = Rio Negro Sustainable Development Reserve, 3 = Anavilhanas National Park, 4 = Rio Negro Right Bank Environmental Protection Area Dark symbols = No-bridge scenario; light symbols = Bridge scenario.



Legend: 1 = Dense lowland rainforest with emergent canopy [*Floresta ombrófila densa terras baixas dossel emergente*]; 2 = Dense alluvial rainforest with uniform canopy [*Floresta ombrófila densa aluvial dossel uniforme*]; 3 = non-forest; 4 = Open alluvial rainforest with palms [*Floresta ombrófila aberta aluvial com palmeiras*]; 5 = Dense aluvial rainforest with emergente canopy [*Floresta ombrófila densa aluvial dossel emergente*]; 6 = Pioneer formations with fluvial or lacustrine influence-herbaceous without palms [*Formação pioneiras com influência fluvial e/ ou lacustre-herbácea sem palmeiras*]; 7 = Dense lowland rainforest [*Floresta ombrófila densa terras baixas*], 8 = Open alluvial rainforest [*Floresta ombrófila aberta aluvial.* Dark symbols = No-bridge scenario; light symbols = Bridge scenario.



Legend: Dark symbols = No-bridge scenario; light symbols = Bridge scenario.

Figure S-6. Values of weights of evidence for each variable.

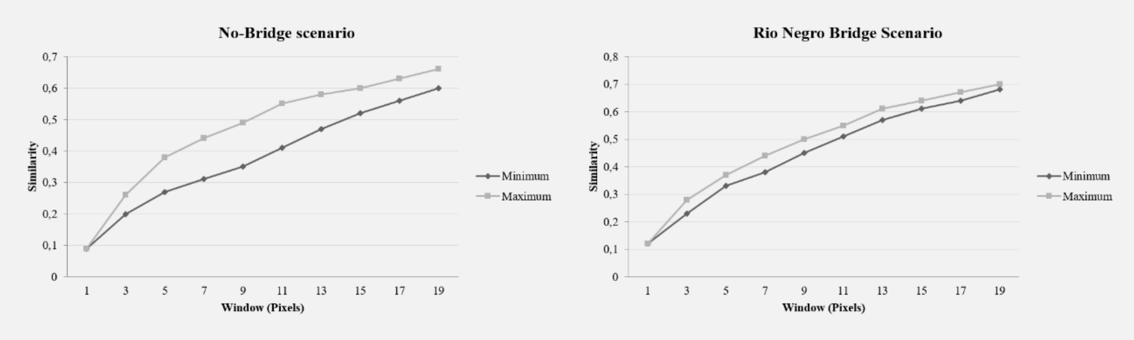


Figure S-7. Spatial validation of deforestation from the comparison between the observed map (Brazil, INPE 2017) and the simulated map for each scenario. Pixel (cell) width = 120 m. Legend: Maximum= more hits, or correct predictions; Minimum= fewer hits.

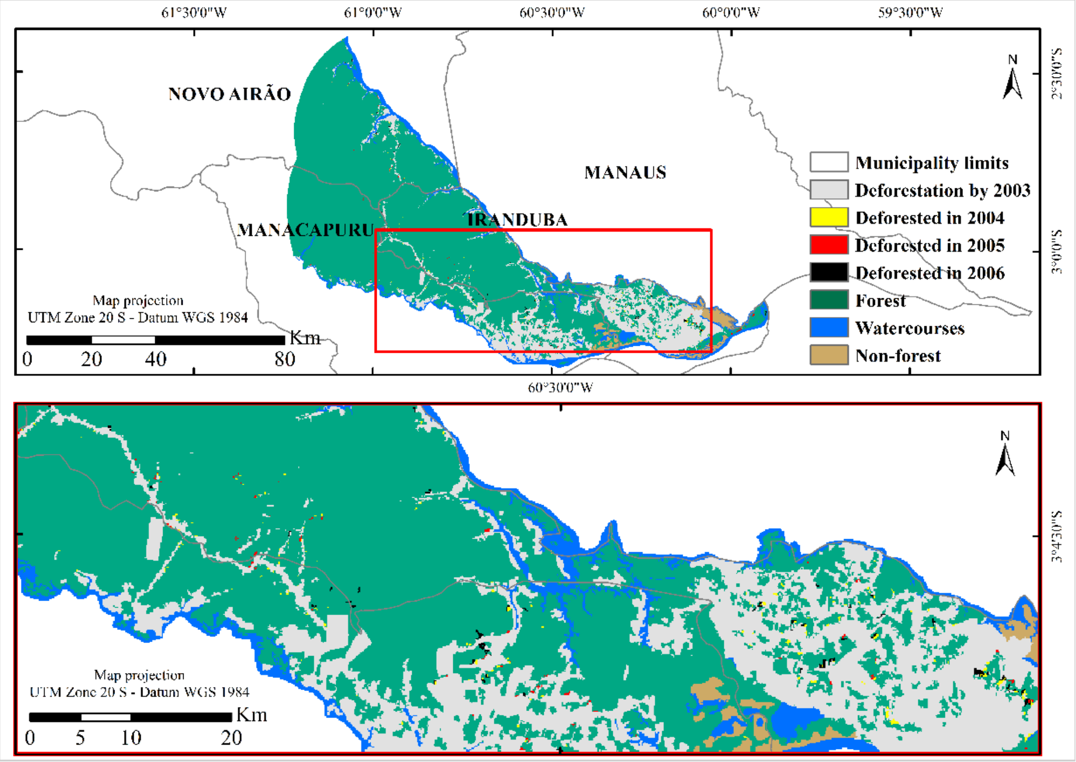


Figure S-8. Map of annual deforestation (Brazil, INPE 2017) for the period used to calibrate the No-bridge scenario (2004 to 2006).

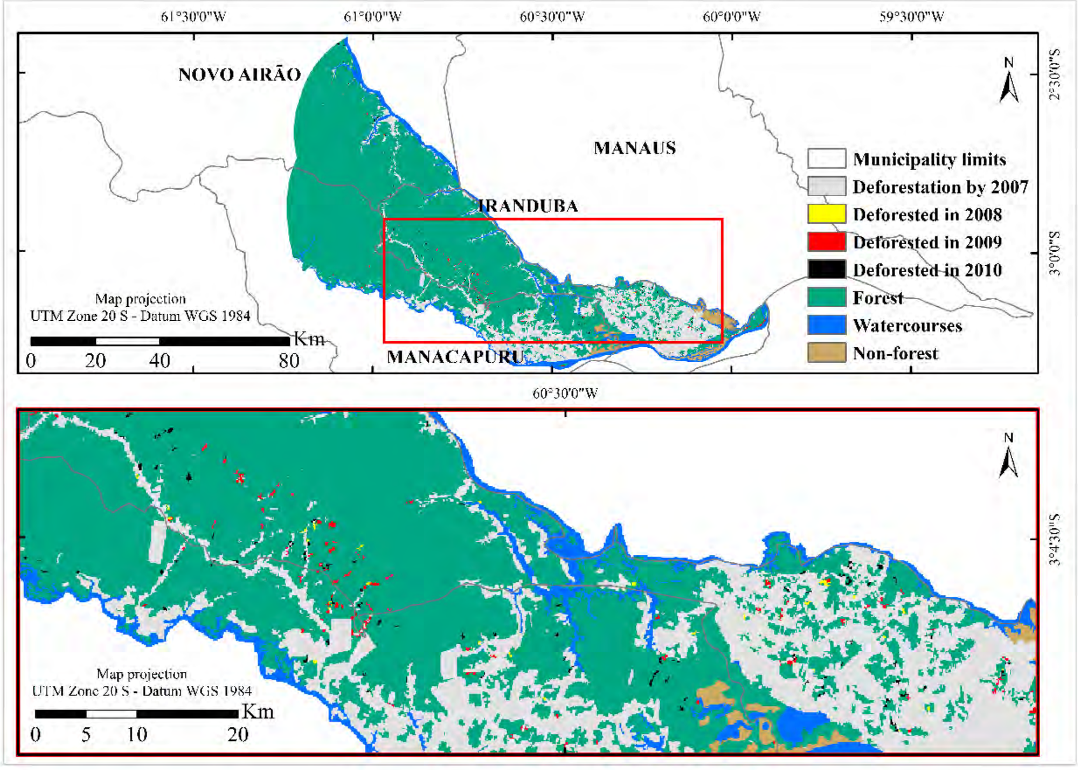


Figure S-9. Map of annual deforestation (Brazil, INPE 2017) for the period used to calibrate the Bridge scenario (2008 to 2010).

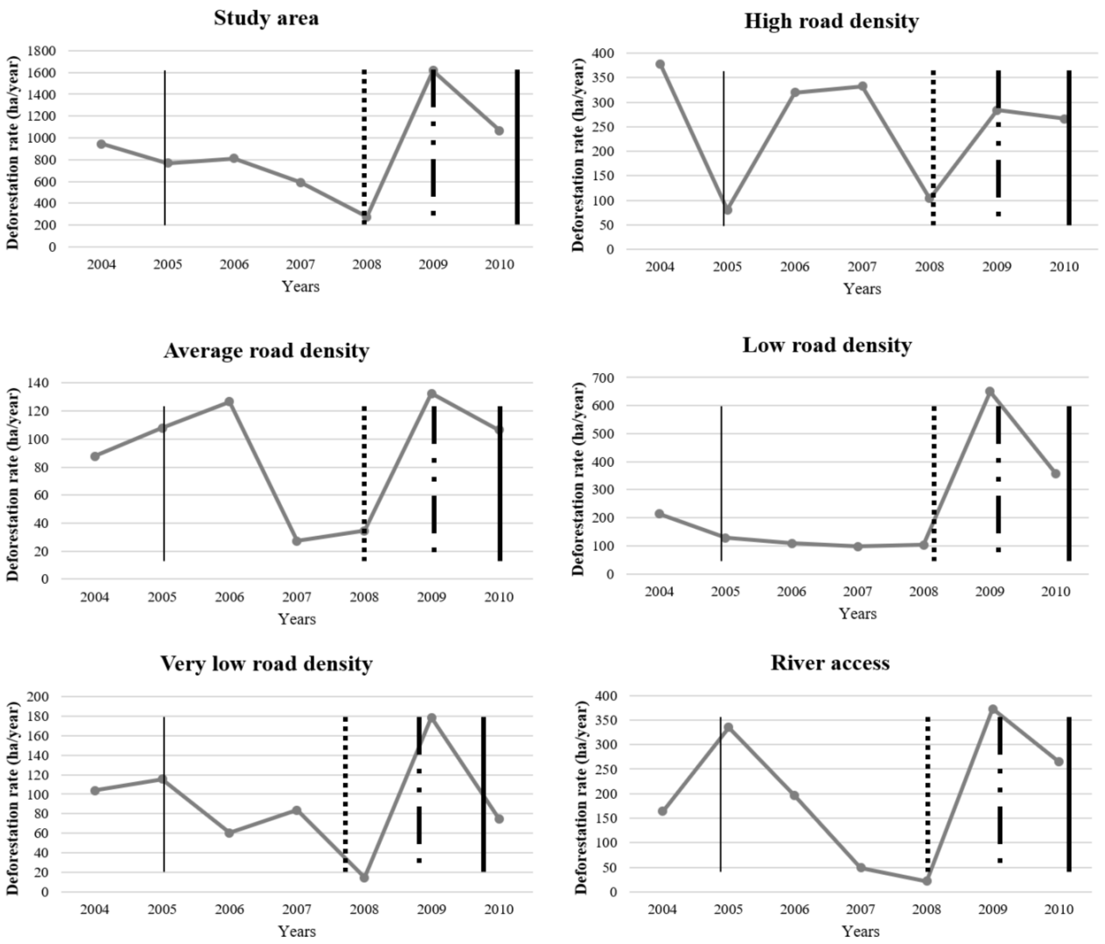


Figure S-10. Deforestation rate by region during the historical period based on data from Brazil, INPE (2017). In the early years, up to the thin line, there is a certain constancy in the deforestation rate. Between the thin line and the dotted line there is a tendency for the rate to decline in the different regions. At the dashed line an increase in deforestation occurs in all regions, followed by a further decline to the thick line.

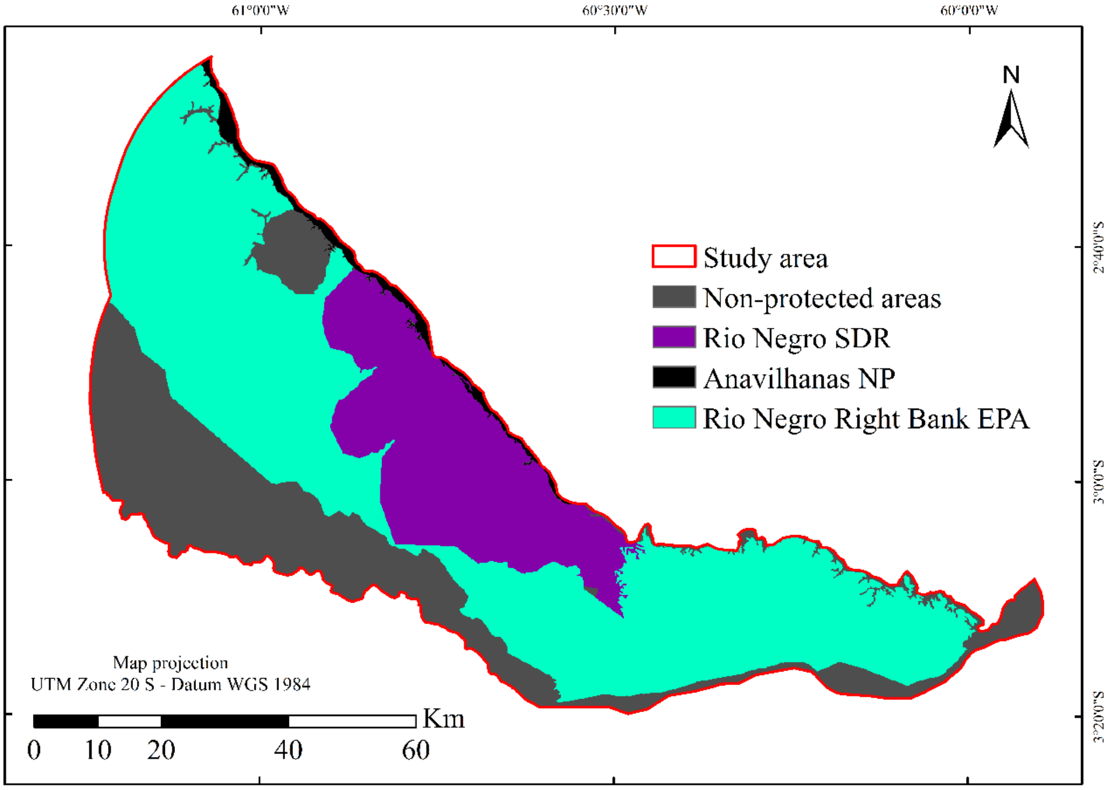


Figure S-11. Protected areas in the study area; data obtained from Brazil, MMA (2015). SDR – Sustainable Development Reserve; NP – National Park; EPA – Environmental Protection Area**.**

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