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Amazon Deforestation and Urban Expansion:

Simulating Future Growth in the Manaus Metropolitan Region, Brazil

Yara L. F. SANTOS[1,2,] Aurora M. YANAI[4], Camila J. P. RAMOS[3], Paulo M. L. A. GRAÇA[4], Jose A. P. VEIGA[2], Francis W. S. CORREA[2], and Philip M. FEARNSIDE[4]

[1]Postgraduate program in Climate and the Environment, National Institute for Research in Amazonia (INPA), Av. André Araújo, 2936, CEP 69067-375, Manaus, Amazonas, Brazil

[2]Postgraduate program in Climate and the Environment, State University of Amazonas (UEA), Av. Darcy Vargas, 1200, CEP 69050-020, Manaus, Amazonas, Brazil

[3]Postgraduate program in Ecology, National Institute for Research in Amazonia (INPA), Av. André Araújo, 2936, CEP 69067-375, Manaus, Amazonas, Brazil

[4]Department of Environmental Dynamics, National Institute for Research in Amazonia (INPA), Av. André Araújo, 2936, CEP 69067-375, Manaus, Amazonas, Brazil

E-mail addresses: yarasantos88@gmail.com (Yara L. F. Santos), yanai@inpa.gov.br (Aurora M. Yanai), camilajramos@gmail.com (Camila J. P. Ramos), pmlag@inpa.gov.br (Paulo M. L. A. Graça), jveiga@uea.edu.br (Jose A. P. Veiga), fcorreia@uea.edu.br. (Francis W. S. Correa), pmfearn@inpa.gov.br (Philip M. Fearnside)

1. Introduction

In 1950, with 54 million inhabitants, Brazil had the largest population in South America. Of this total, 36% of the inhabitants lived in urban areas. In 2019, Brazil still had the largest population in South America, with approximately 210 million inhabitants. Of this total, 99.8 million (48%) lived in integrated regions of development and/or urban agglomerations (IBGE, 2019a). According to the United Nations, by 2050 approximately 90% of the Brazilian population will reside in urban areas (United Nations, 2019).

Urban growth implies physical and functional changes due to the transition from rural to urban forms. This process consists of complex non-linear interactions among various components, including topography, rivers, land use/cover, transport, culture, population, economy, and infrastructure (Pavão, 2017). Moreover, the disorderly urban growth can cause a number of environmental and social problems. In the environmental sphere, for example, the following implications can be highlighted: 1) reduction and fragmentation of green areas with respective reduction of local fauna and flora (Allen, 2003; Ramos et al., 2018); 2) erosion and contamination of rivers and tributaries that can produce an environmental imbalance - eutrophication, reduction of biodiversity, waterborne diseases, among other effects (Fonseca et al., 2016; Costa et al., 2020; Paiva et al, 2020); 3) decrease in soil permeability that, consequently, can increase the occurrence of floods (Tucci, 2008); 4) increase in respiratory diseases as a result of the intensification of soil and air pollution (Ignotti et al., 2010) and; 5) increase in surface and air temperature, implying the so-called urban heat island effect (Kalnay & Cai, 2003; de Souza, & dos Santos Alvalá, 2014). In the social scenario we highlight the lack of housing that leads to the emergence of slums and/or the construction of housing in irregular locations, unemployment, increased violence and social exclusion (Allen, 2003; Souza, 2015).

In the Amazon, the urbanization process first occurred by rivers, which are an important transport route in the region (Sant'Anna, 1998; Resende, 2006; Kuwahara et al., 2012; Góes Filho, 2015). Most Amazonian cities are still located along rivers or in coastal areas (Costa, 2000). However, in the 1960s and 1970s, the Brazilian federal government started to build highways in the Amazon, such as the BR-230 (Transamazon Highway), BR-010 (Belém – Brasília), BR-319 (Manaus – Porto Velho), and the BR-174 (Manaus – Boa Vista). This facilitated agricultural, mineral, timber, and industrial projects in the region and consequently rural exodus from various parts of the country to urban centers in the Brazilian Amazon (Costa, 2000; Barbieri & Carr, 2005; Becker, 2005; Schor & Oliveira, 2011; Costa et al., 2019). Despite its low demographic density, the population in the Brazilian Amazon increased from around 8.2 million in 1970 to 24 million in 2010, a growth of 193% (IBGE, 2010). This population growth was concentrated in urban centers and became one of the largest environmental problems in the region due to rapid migration as well as a lack of planning and infrastructure (Becker, 2001).

The Manaus Metropolitan Region (MMR), created on May 30, 2007, has different characteristics from other Brazilian metropolitan regions (Guedes et al., 2009). The MMR is located in the center of the largest Brazilian biome – the Amazon biome (MMA, 2019). In this region, the municipal (county) seats are distant from each other, usually separated by the forest or rivers. Infrastructure, such as the Jornalista Phelippe Daou Bridge (the Rio Negro Bridge, opened in 2011), which connects Manaus to Iranduba, produced profound changes in land-use/cover in these municipalities. In the municipality of Iranduba, planned neighborhoods emerged and the Manuel Urbano highway (AM-070), connecting Manaus to

Iranduba, Manacapuru, and Novo Airão, was duplicated to form a divided highway. A peri-urbanization process occurred in theses municipalities, altering the physiognomy of their landscapes. Peri-urban areas are characterized by having urban, rural, and natural elements at different levels (Allen, 2003; Moreira et al., 2016). Ramos et al. (2018) analyzed the peri-urbanization process on the right bank of the Rio Negro after the inauguration of the Rio Negro Bridge and simulated deforestation up to 2030 in the municipalities of Iranduba, Manacapuru, and Novo Airão. Their results show that the most vulnerable areas to deforestation are those with the combination of ample available forest and an expanding road network far from large urban centers.

Land-use change processes are expected to accelerate in the coming decades (Ritchie & Roser, 2018). Thus, the increased migration to urban areas, housing scarcity, and insufficient infrastructure require urban regions to constantly monitor and plan land-use change (Thapa & Murayama, 2011a). Understanding how the urban growth process occurs in the MMR is necessary because the few studies that exist focus only on the city of Manaus (Powell et al., 2007; Imbiriba et al., 2009; Souza et al., 2016). In addition, the MMR's location in the middle of a tropical forest makes this area relevant to biodiversity and ecosystem services at the regional and global level. This region still has large areas of continuous forest; but the new dynamics of land-use/cover change heighten the vulnerability of the Amazon. The objective of this study is to investigate how land-use/cover change could occur in the MMR up to the end of the 21st century, with an emphasis on urbanization.

2. Material and Methods

2.1 Study Area

The Manaus Metropolitan Region (MMR) encompasses 13 municipalities in the Brazilian state of Amazonas: Autazes, Careiro, Careiro da Várzea, Iranduba, Itacoatiara, Itapiranga, Manacapuru, Manaquiri, Novo Airão, Presidente Figueiredo, Rio Preto da Eva, Silves, and Manaus (Fig. 1). These municipalities cover an area of 127,000 km^2, or 8% of the state of Amazonas (IBGE, 2019b). Of the 13 municipalities, Manaus, the capital of the state, is the largest urban area, with around 400 km^2, and approximately 82% of the total population of the MMR. Manaus is the seventh most populous municipality in the country, with approximately 2,182,763 inhabitants in 2019 and an annual population growth rate of 1.7% (IBGE, 2019b).

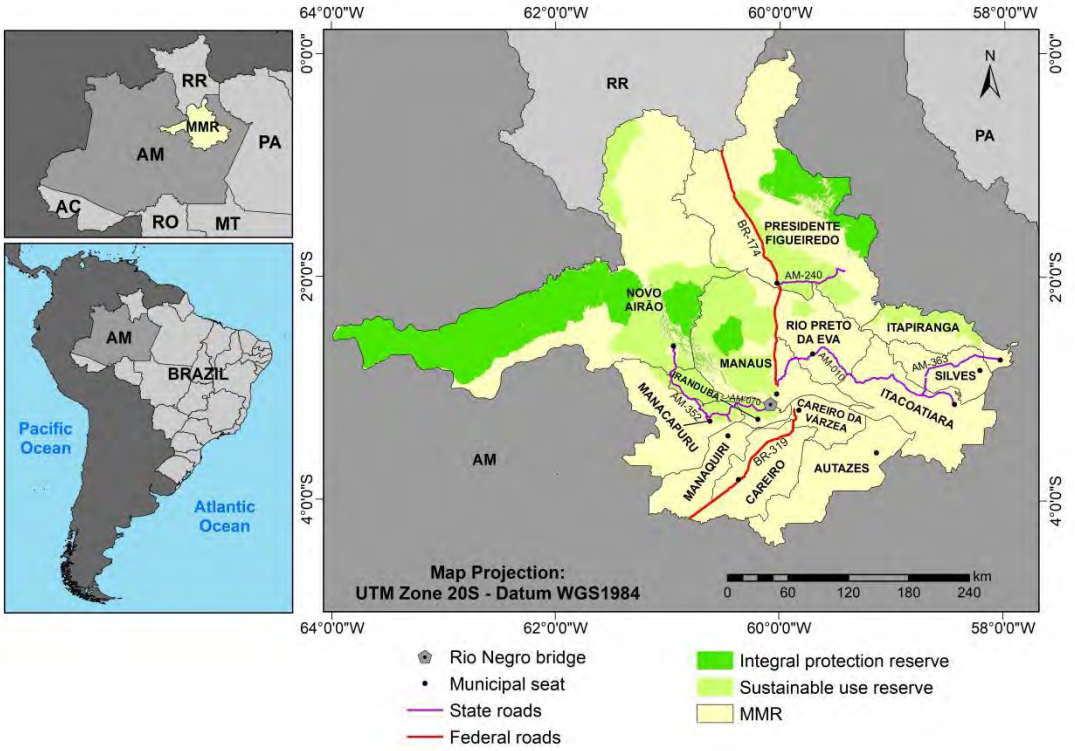

Fig. 1. Study area.

2.2 Spatial model of deforestation and urban expansion

To simulate deforestation and urban expansion in the MMR up to 2100, a spatial model of land-use/cover change used was developed in the environmental modeling platform Dinamica EGO (version 5.0.0). Dinamica EGO (Environment for Geoprocessing Objects) is free software developed by the Remote Sensing Center (CSR) of the Federal University of Minas Gerais (UFMG). It has been used to model land-use/cover change in the Amazon (Soares-Filho et al., 2002, 2006; Gonçalves, 2008; Fearnside et al., 2009; Yanai et al., 2012; Ramos et al., 2018; Osis et al., 2019), urban expansion and intra-urban dynamics (Almeida et al., 2003, 2008; Young, 2013), and fire propagation (Silvestrini et al., 2011; Soares-Filho et al., 2012; Brando et al., 2014, 2020; Faria et al., 2017).

Modeling in Dinamica EGO is of the cellular-automaton type. This means that to change the state of a cell (pixel) the model explicitly takes into account the state of neighboring cells following transition rules (Soares-Filho et al., 2002; Yeh & Li, 2006). All cells are evaluated simultaneously at each time step (Xie, 1996; Sirakoulis et al., 2000; Yeh & Li, 2006; Pontius Jr. et al., 2008).

The modeling steps consisted of (1) obtaining the input data, (2) calibrating and validating the model, and (3) simulating deforestation and urban expansion from 2017 to 2100, based on a business-as-usual (BAU) scenario. In this scenario, the rates and spatial patterns of deforestation and expansion of urban areas in each municipality analyzed follow the trend observed from 2004 to 2010. This period includes the effect of the Rio Negro Bridge, including the planning period that began in early November 2003 and the bridge construction from its initiation in December 2007 until close to the inauguration of the bridge in October 2011. The effect of the bridge, especially in the municipalities of Iranduba and Manacapuru, was to an increase land speculation and the occupation of new areas, with the

potential for expanding deforestation and for driving socioeconomic transformations. Because the beginning of construction of the bridge in 2007 already led to increased real estate speculations and deforestation, a recent study used the period from 2008 to 2010 to assess the effect of bridge in a simulation of deforestation (Ramos et al., 2018).

2.3 Input data

In our model the cartographic data were in raster format with a spatial of 100 m, in which each cell had an area of 1 ha. The UTM (Universal Transverse Mercator) cartographic projection was used, corresponding to the UTM 20 South zone and Datum WGS 1984. The model used land-use/cover maps in the calibration (maps of 2004 and 2010), validation (2012 and 2017), and simulation (2017-2100) stages.

Land-use/cover maps were based on data from the Amazon Deforestation Monitoring Project (PRODES) and the TerraClass project at the National Institute for Space Research (INPE) (Supplementary Material, Appendix 1). In the present study, the urban area class was derived from the TerraClass project (INPE, 2017) for 2004, 2010, and 2012. Due to the lack of TerraClass data for 2017, we used data from the previous years from TerraClass and updated the urban area with data from the classification made by the MapBiomas project (MapBiomas Project, 2018) and visual interpretation of satellite images from the Google Earth Pro program (Google Earth Pro, 2018). MapBiomas data were also used to reduce the loss of information in areas covered by clouds, identifying the classes of interest in these areas. Figure 2 presents a schematic of the methodology used to obtain land-use/cover map of the MMR for 2017.

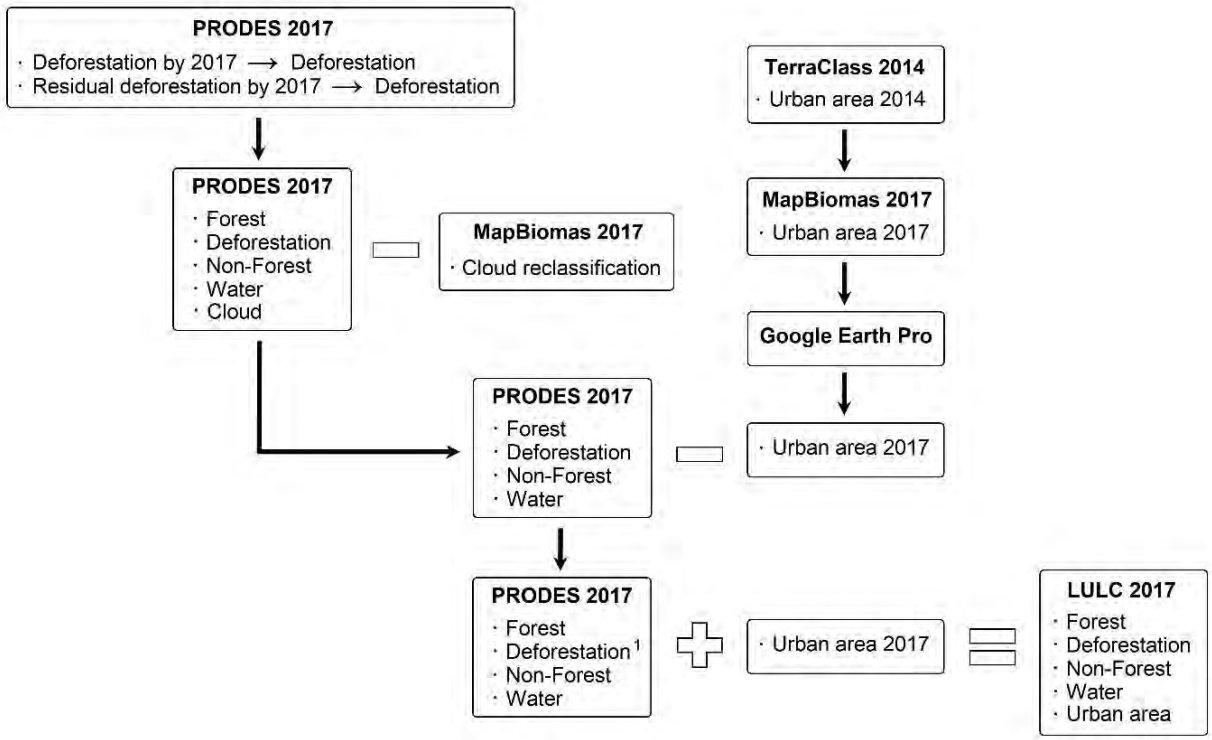

Fig. 2. Methodology for obtaining the 2017 land-use/cover map. The residual deforestation class corresponds to errors of omission in the PRODES mapping of previous years (Guerra et

al., 2010). Deforestation is the deforestation of PRODES without overlapping with the urban area.

In addition to the land-use/cover maps, other environmental spatial variables that influence deforestation and urban growth were required. The static variables used were elevation, slope, conservation units (protected areas for biodiversity), settlements (government-organized colonization projects for small farmers), quilombola areas (traditional territories of the descendants of escaped African slaves), indigenous lands, special areas (parks and military area), distance to rivers, distance to main highways, soil, and vegetation (Fig. 3). These variables do not change during model simulations.

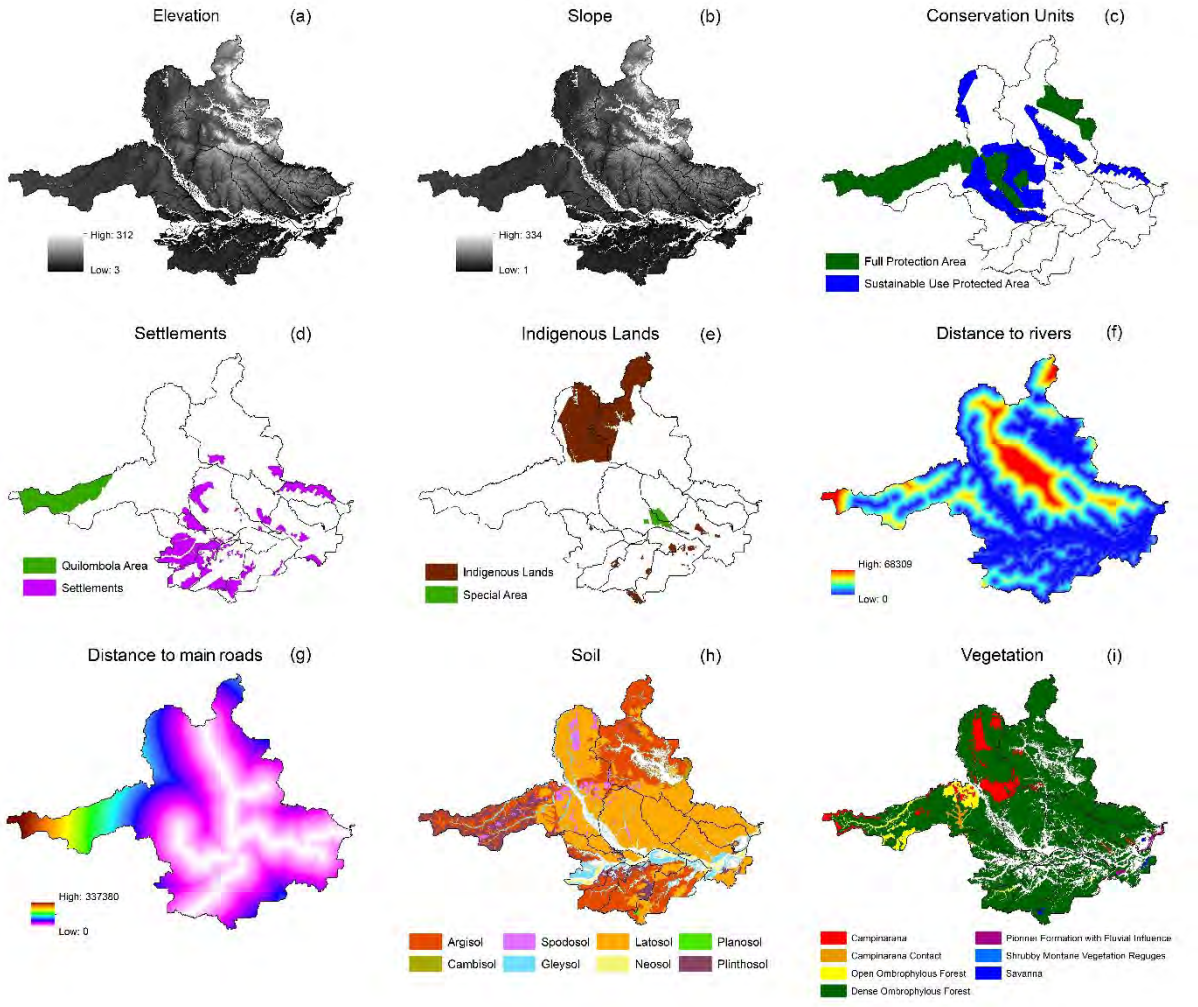

Fig. 3. Static variables used in the model: (a) Elevation, (b) Slope, (c) Conservation units, (d) Settlements and Quilombola Area, (e) Indigenous lands and Special areas, (f) Distance to rivers, (g) Distance to the main highways, (h) Soil, and (i) Vegetation. The distance and elevation variables are expressed in meters while the slope is in degrees.

The maps of distance to deforestation, distance to the urban area (central and non-central), and distance to secondary roads are considered to be dynamic variables because they are updated during the simulation. Distance to non-central urban areas are areas considered urban in the TerraClass project that are located away from the municipal seat. The dynamic variables and the maps of conservation units (protected areas for biodiversity), settlements

(areas where the government distributes parcels of lands to small farmers) and a quilombola area (an area traditionally occupied by descendants of escaped African slaves) were used to create the maps of the attractiveness and friction maps (see Supplementary Material, Appendix 2). The maps used as input for the model are described in Table 1.

Table 1. Sources of maps prepared as input to the land-use/cover model.

Input data	Source
Land-use/cover maps (2004, 2010, 2012, and 2017)	▪ PRODES – Amazon Deforestation Monitoring Project (PRODES, 2019); ▪ TerraClass is program complement to PRODES by adding information about land use and land cover in areas with clear-cutting mapped by PRODES (INPE, 2017); ▪ MapBiomas – MapBiomas Project – Collection 3 of the Annual Series of Land Coverage and Use Maps of Brazil (MapBiomas Project, 2018); ▪ Google Earth Pro (Google Earth Pro, 2018).
Maps of static variables	▪ Elevation – SRTM – Shuttle Radar Topography Mission; ▪ Slope – EMBRAPA – Brazilian Agricultural Research Corporation; ▪ Conservation Units – MMA – Ministry of the Environment; ▪ Settlements – INCRA – National Institute for Colonization and Agrarian Reform; ▪ Quilombola Areas – INCRA – National Institute for Colonization and Agrarian Reform; ▪ Indigenous lands – FUNAI – National Indian Foundation; ▪ Soil – EMBRAPA – Brazilian Agricultural Research Corporation; ▪ Vegetation– IBGE – Brazilian Institute for Geography and Statistics; ▪ Distance from rivers* – PRODES – Amazon Deforestation Monitoring Project.
Maps of dynamic variables	▪ Distance to deforestation* – PRODES; ▪ Distance to the urban area* – TerraClass and MapBiomas; ▪ Distance to the nearest non-central urban area* – TerraClass and MapBiomas; ▪ Distance to highways and secondary roads* – DNIT – National Department of Transport Infrastructure, IBGE – Brazilian Institute for Geography and Statistics and – United States Geological Survey – USGS – by visual interpretation of satellite images.

*The distance was calculated using a "Calc to Distance Map" functor in Dinamica EGO.

2.4 Model calibration and validation

The land-use/cover change model was regionalized according to municipal limits. Thus, each municipality has its own parameters for the amount of area to be deforested and the urban area to be expanded. Transition rates were calculated for changes in the status of the forest to deforestation and for deforestation to urban areas (Supplementary Material, Table S-2). The period from 2004 to 2010 was used in the calibration phase, and 2012 to 2017 for the model validation.

In this study, we considered the annual rates of transitions from forest to deforestation and deforestation to urban areas. The deforestation rate for year "t" is multiplied by the extent

of the remaining forest in year "t – 1" to obtain the area to be deforested in year "t" (Soares-Filho et al., 2009). The same procedure was employed for the urban growth rate.

Dinamica EGO features two algorithms for spatial allocation of the status changes produced by the expander and patcher transition functions. The expander function represents the expansion of previously existing patches, while the patcher function creates new patches through a seeding mechanism in which an initial set of pixels is generated to form new patches (Soares-Filho et al., 2002). We established that 20% of the transition from forest to deforestation would be in expander mode and the remainder in patcher mode. To better represent the expansion pattern of the urban area, we established that 90% of the transition from deforestation to urban area would be in the expander mode.

The calculation of transition probability maps employed the statistical weight of evidence method. The transition probability maps present the most favorable areas for a transition to occur, for example, from forest to deforestation (Soares-Filho et al., 2002). To apply the weights-of-evidence method, the static and dynamic variables must be independent of each other (Bonham-Carter et al., 1989). The analysis of the correlation between the variables employed tests in pairs based on the Cramer coefficient and the Joint Information Uncertainty. In this study, values above 0.5 were considered as dependent variables (Bonham-Carter, 1994). When this occurs, one of the two variables must either be ignored or the two must be combined into a third variable (Soares-Filho et al., 2009). In this study, the environmental variables – conservation units and special areas (forest reserves and military areas) – showed a correlation in most municipalities of the MMR. Thus, a third map combining these variables was created. In addition, the municipality of Itacoatiara showed a correlation between the dynamic variables "distance to the central urban area" and "distance to non-central urban areas;" in this case we decided to keep the variable "distance to central urban areas" because it has a more significant correlation with changes in land use/cover than did "distance to non-central urban areas."

The model was validated using the reciprocal similarity comparison technique that was developed by Soares-Filho et al. (2009) from an adaptation of the fuzzy similarity method (Hagen, 2003). The similarity between maps (observed and simulated) can range from 0% to 100%, where 0% indicates that the maps are completely different from each other and 100% indicates that they are identical (Soares-Filho et al., 2009; Walker et al., 2010). As a result, two values are obtained, 'minimum similarity' and 'maximum similarity'. This is because two comparisons are made, one based on the observed map and the other based on the simulated map, which can result in two similarity rates, a higher and a lower one. In this study, we adopt the minimum similarity value as the reference. The parameter used to assess similarity was set to constant decay, where a value of 1 refers to the similarity value if the corresponding cells are found in the search window, and zero if they are not found (Soares-Filho et al., 2009). In this approach, values above 50% similarity are considered satisfactory for validation of a model (Ximenes et al., 2008; Vitel et al., 2009; Thapa & Murayama, 2011b; Yanai et al., 2012; Barni et al., 2015; Ramos et al., 2018; Osis et al., 2019).

Validation was carried out from a simulation for the period from 2012 to 2017 with transition rates and weights-of-evidence coefficients for the period from 2004 to 2010. We chose a validation period different from the calibration period to avoid the spurious effect of using the same transition rates in these two stages (Paegelow et al., 2018). In addition to the validation for 2017, we also compared our results with a null model. In this model, the same input maps and transition rates were used, but the coefficients of the weight s-of-evidence

have been set to zero. This process generates random probability maps for each simulated year. In other words, the probability of a transition occurring is 50% (Soares-Filho, 2015; Osis et al., 2019). A summary of the settings used in this study is available in the Supplementary Material (Table S-3 and Appendix 3).

3. Results

3.1 Validation of the model

The minimum similarity values as a function of the number of windows are presented in Figure 4. The larger the size of the windows, the greater the similarity between the observed and simulated maps. The highest similarity values occurred for the 2017 simulations in non-random mode. This indicates that the adjustments made in the calibration represent an improvement in the spatial distribution of the simulated deforestation and in the urban expansion patches as compared to the null model in which the transitions occur in a random manner (Osis et al., 2019). The values of minimum similarity for the non-random simulation ranged from 17.4% (1×1 window) to 79.0% (19×19 window). For the 2017 simulation, in the random condition, the minimum similarity values ranged from 8.2% (1×1 window) to 50.7% (19×19 window). The 2017 simulations, in non-random mode, reached acceptable values (above 50%) in the seventh window (0.7 km of resolution).

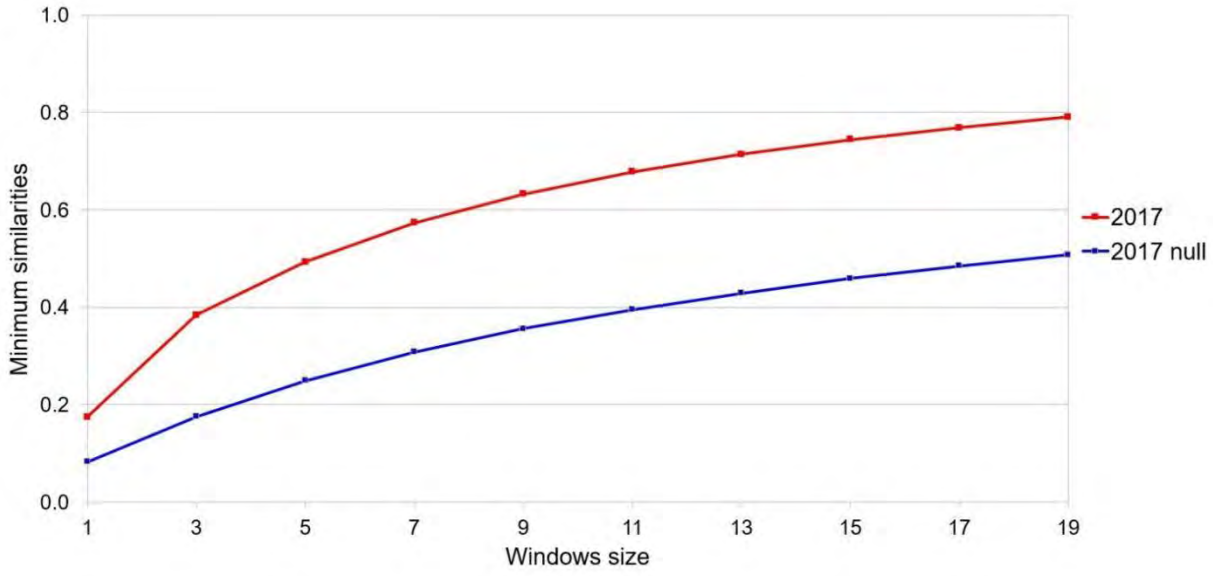

Fig. 4. Minimum values of fuzzy similarity with multiple resolution adjustment using the constant decay function. “Window size” is the number of cells (pixels) on each side of the square window area.

The observed and simulated maps of land-use/cover for the year 2017, with the urban area of Manaus centralized, are displayed in Figure 5. Note that the model adequately represented the change in land-use/cover in the region presented.

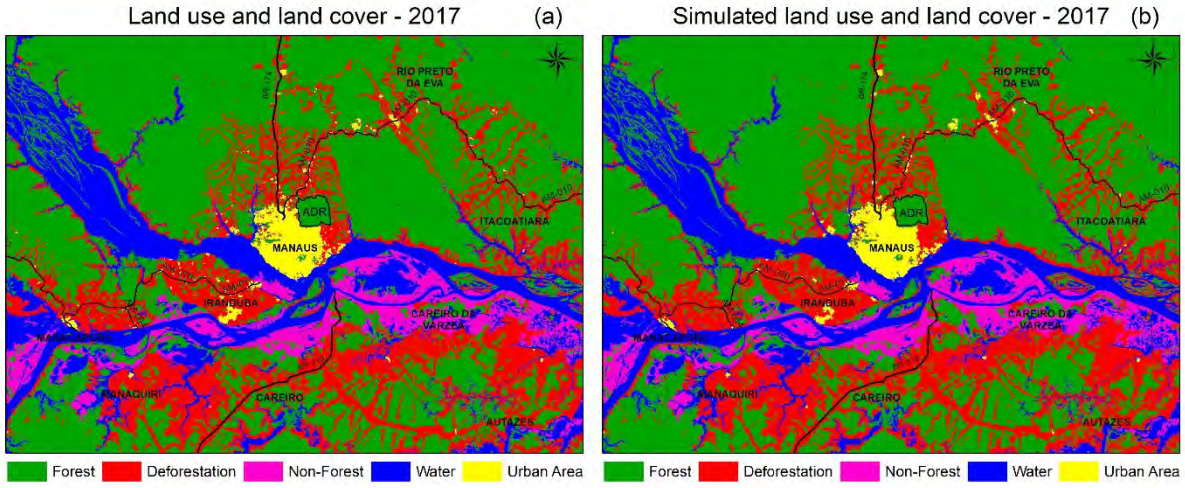

Fig. 5. Expanded detail comparing the observed and simulated land use maps for 2017, with emphasis on the Adolfo Ducke Reserve (ADR) area located in the urban area of Manaus (in the center).

The land-use/land-cover data from observed and simulated maps for the MMR, for the year 2017, as well as their percentage differences are presented in Table 2. The total percentage difference between the maps has an absolute value of 7.2%. The forest class showed the smallest percentage difference. The model overestimated the deforestation class and underestimated the forest and urban area classes.

Table 2. Land-use/land-cover data for the MMR in 2017 from observed and simulated maps.

Area (km^2) – 2017				
Class	**Observed**	**Simulated**	**Absolute difference (simulated map – observed map)**	**Percentage difference (%)**
Forest	99,115.5	98,703.4	-412.0	-0.4
Deforestation	11,227.8	11,655.5	427.8	3.8
Urban	525.7	510.0	-15.7	-3.0

Figure 6 charts the differences between the simulated and observed maps, for each municipality of the MMR in 2017. For the deforestation class (red bars), the model achieved percentage differences of less than 10% between the observed and simulated maps. For this class, the municipality of Novo Airão had the smallest percentage difference (-0.1%). The municipalities of Manaus and Rio Preto da Eva both showed percentage differences of less than 1%. On the other hand, the municipality of Itapiranga exhibited the largest percentage difference (9.4%). For the urban class (blue bars), the model displayed greater differences between the simulated map and the observed map. The municipality of Careiro da Várzea had a relatively high percentage difference (-64.5%) for the urban area, while the municipality of Manaus had the smallest percentage difference (-0.2%). More than half of the municipalities (Autazes, Careiro, Itacoatiara, Manaus, Novo Airão, Presidente Figueiredo and Rio Preto da Eva) showed a difference below 10%. Note that the denominators from which these percentages are calculated vary widely among the municipalities, with Manaus having by far the largest initial urban area.

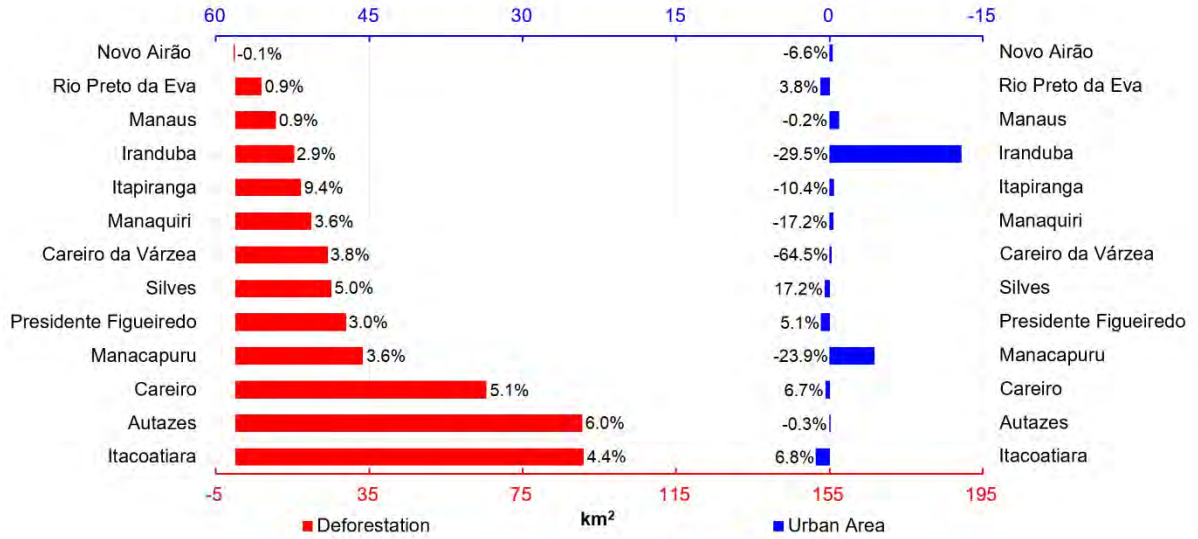

Fig. 6. Difference between the simulated and observed maps of the MMR municipalities for the year 2017. The left side (red bars) represents the deforestation class (km^2), and the right side (blue bars) represents the urban area class (km^2).

3.2 Space-time dynamics of deforestation and urban expansion

Figure 7 illustrates the change in land-use/cover of the MMR for the period from 2017 to 2100 with the urban area of Manaus located in the center of the domain. The expansion of urban areas (in yellow) and the increases in deforested area (in red) along state and federal highways are evident. The magnitudes of growth in deforestation and in the urban areas of the municipalities of Manaus, Iranduba, and Manacapuru also stand out. In the case of deforestation, the expansion is more accentuated to the south of Manaus, in the region with the municipalities of Careiro da Várzea, Careiro, and Manaquiri (Figures 7a–d). As of 2050, the municipalities of Iranduba and Manacapuru display an increase in their deforested area and a slight increase in their urban areas, especially in the last decades of the 21st century. The municipalities to the south and southeast of Manaus show a significant expansion of their deforested areas between 2050 and 2070 (Figures 7e–g). Towards the end of the 21st century, the urban expansion of the city of Manaus to the north is observed, along the BR-174 and AM-010 highways. In addition, the preservation of the protection area can be noted throughout the MMR, as in the case of the Adolpho Ducke Forest Reserve (ADR) in Manaus (Figures 7h–j).

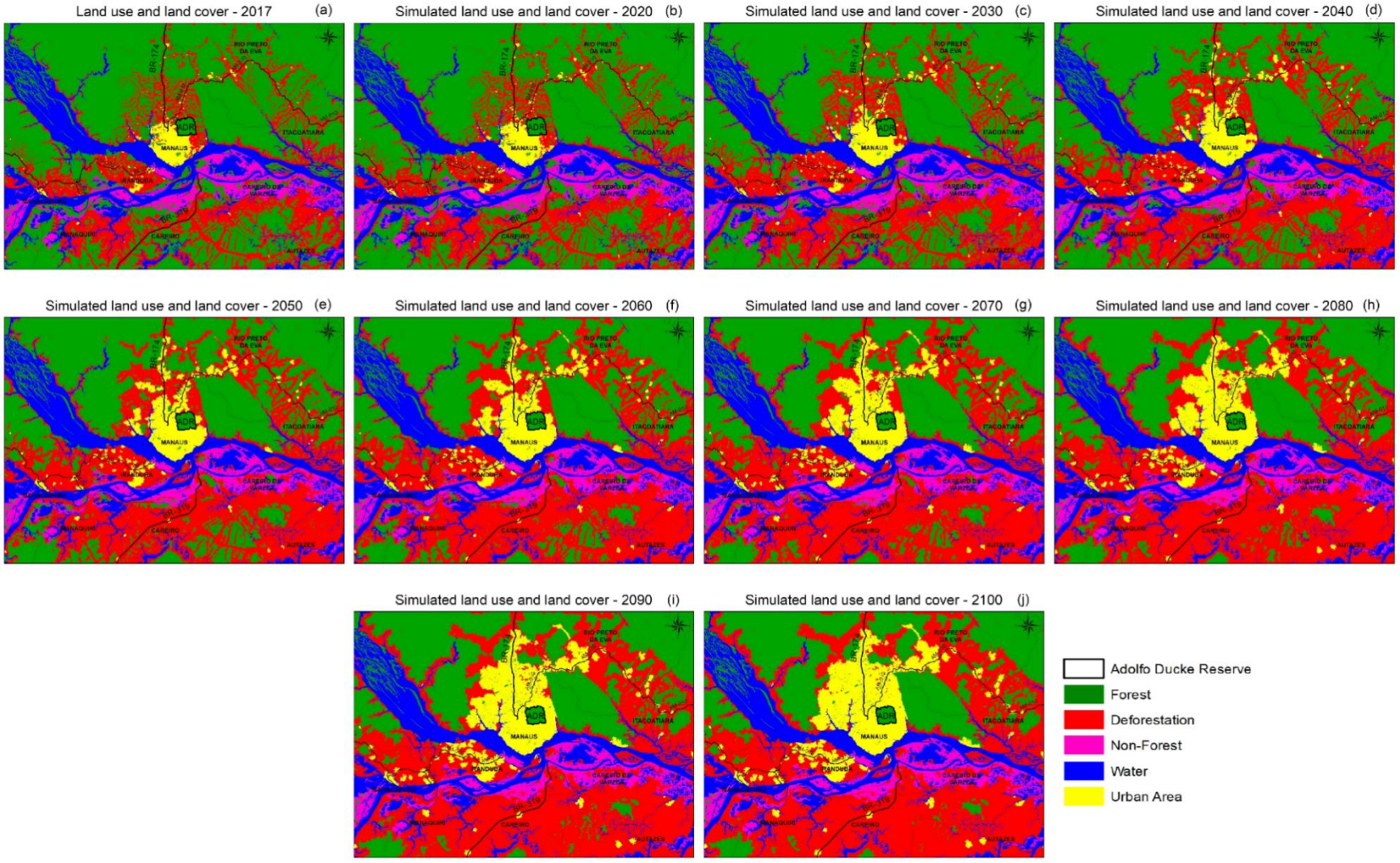

Fig. 7. Spatial evolution of the MMR land-use/cover, for the period from 2017 to 2100, with the urban area of Manaus in the center.

The data from the simulated land-use/land-cover maps of the MMR for the period from 2017 to 2100 are provided in Table 3. By 2100, the MMR endures an 18% reduction in forest cover, corresponding to 18,200 km^2 compared to 2017. The deforested area increases, approximately, 137% (about 15,300 km^2) in relation to 2017 and urban area 555% (3000 km^2) for the same period.

Table 3. Temporal evolution of the MMR land use/cover for the period from 2017 to 2100.

Area (km^2)										
Class	**2017**	**2020**	**2030**	**2040**	**2050**	**2060**	**2070**	**2080**	**2090**	**2100**
Forest	99,115.5	98,259.3	95,539.8	93,009.6	90,649.0	88,441.2	86,371.5	84,427.2	82,596.8	80,870.6
Deforestatio	11,227.8	12,016.0	14,482.2	16,721.4	18,758.1	20,613.0	22,304.9	23,849.6	25,261.6	26,553.4
Urban	525.7	593.6	846.9	1,137.9	1,461.9	1,814.7	2,192.6	2,592.2	3,010.5	3,445.0

By 2100, all MMR municipalities would have reduced their forest area. The municipalities Careiro da Várzea, Itacoatiara, Iranduba, and Autazes display percentage forest losses above 50% by the end of the century. The municipalities that presented the greatest reduction of forest cover are: Itacoatiara (59.1% or 2695.5 km^2), Autazes (52.8% or 2545.0 km^2), Presidente Figueiredo (11.5% or 2433.2 km^2), and Manaus (27.1% or 2299.9 km^2). The forest area in the municipality of Novo Airão experiences the least impacted due to deforestation by 2100 (1.2% or 433.8 km^2) (see Supplementary Material, Figure S-2).

The absolute growth in km^2 for the deforestation area (red bars) and urban area (blue bars) of the MMR municipalities and their respective relative values for the period 2017–2100 are depicted in Figure 8, and the growth values of deforestation and urban area spatially distributed in the municipalities are illustrated in Figure 9.

In 2100, the municipalities of Novo Airão, Presidente Figueiredo, and Itapiranga present an increase greater than 200% in deforested area, compared to 2017, with Novo Airão being the municipality with the highest rate of deforestation growth in percentage terms. In terms of deforested area, Itacoatiara, Autazes, and Presidente Figueiredo are the municipalities that exhibit increased deforestation above 2000 km^2 by 2100 (Figure 9a).

All municipalities analyzed would increase their urban area by the end of the 21st century by over 1000% compared to 2017, with the exception of Manaus and Manaquiri (Figure 8). The municipalities of Manaus, Rio Preto da Eva, Iranduba, and Presidente Figueiredo experience the greatest growth in urban area in terms of area (> 200 km^2) by 2100. Careiro da Várzea is the municipality that experiences the lowest urban growth (less than 1 km^2) (Figure 9b).

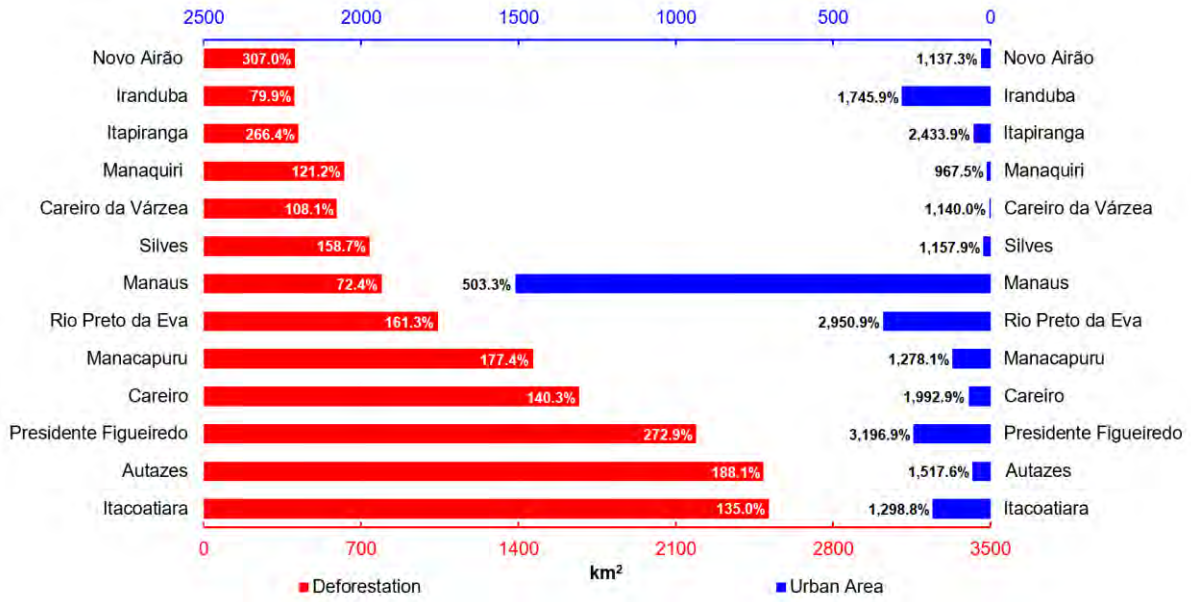

Fig. 8. Growth of the deforestation area and urban area of the MMR municipalities from 2017 to 2100. Deforestation (km^2) is represented by the red bars (left side) and the lower axis, while the urban area (km^2) is represented by the blue bars (right side) and the upper axis.

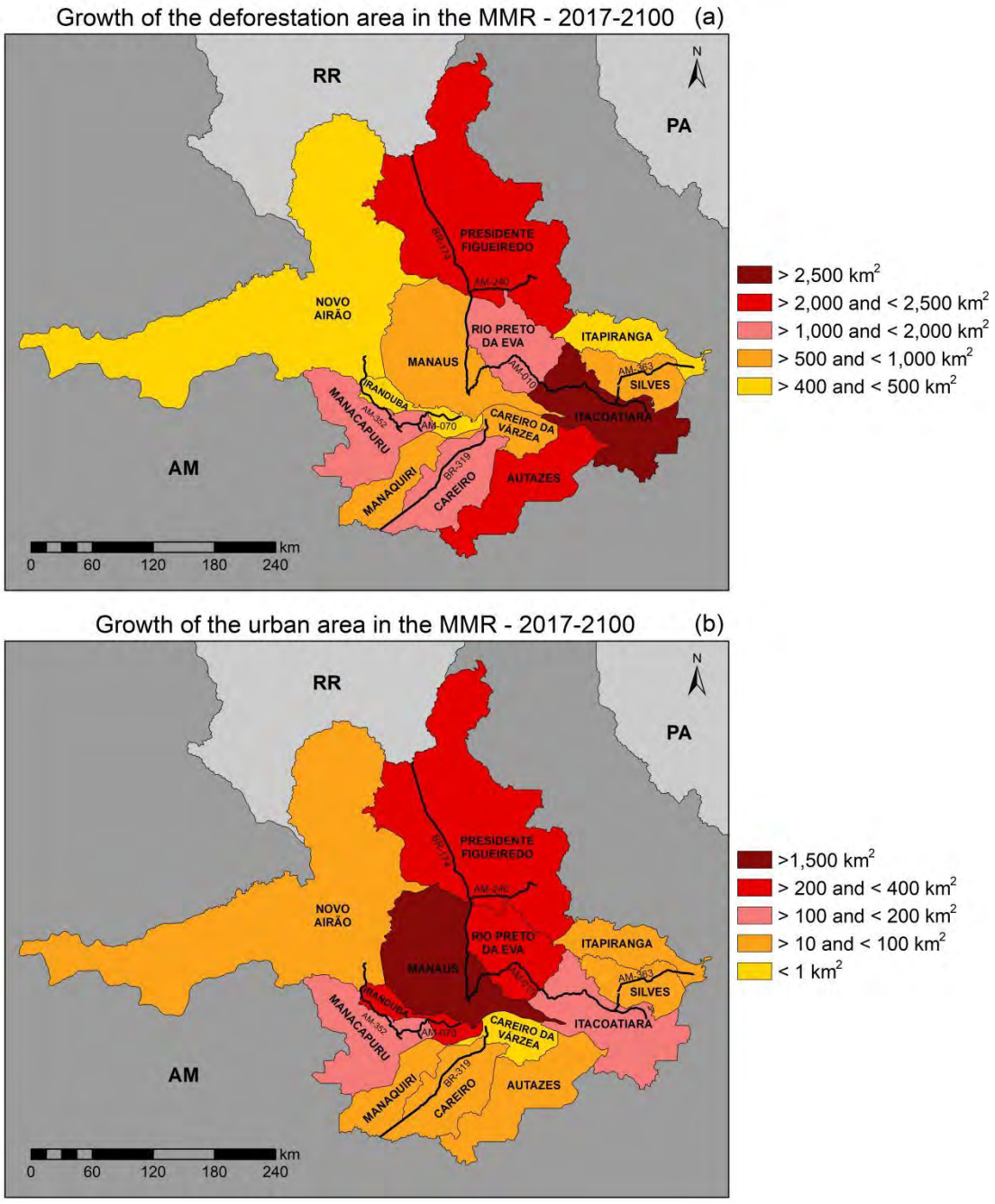

Fig. 9. Spatial distribution of growth in the deforestation area (a) and urban area (b) of the MMR municipalities from 2017 to 2100..

4. Discussion

The minimum similarity results obtained are within the validation range found in other studies conducted with Dinamica EGO software as presented in Supplementary Material, Table S-1. The window for which the similarity reached 50% is presented for each study.

The large variations in deforestation rates in the Amazon must be considered (Supplementary Material, Figure S-2). The highest peak of deforestation in the Amazon region occurred in 2004, but rates decreased dramatically after that year. In the study area, the rate decreased slightly, but for some municipalities 2008 had one of the highest deforestation rates. The calibration included this period of high deforestation rates for the study area. The lowest point of deforestation for the Legal Amazon occurred in 2012. The study area also experienced one of the lowest deforestation rates in 2012, followed by a fall in the rate for many municipalities in 2013, with trend of increasing rates in the following years.

The validation covers the period from 2012 to 2017. From 2018 onwards, a strong trend of increasing deforestation in the Amazon has been observed, with different rates than in the mid-2000s. Waves of deforestation are common trends, as deforestation rates are subject to several factors, including economic cycles, election cycles (both regional and local), environmental protection policies, and changes in infrastructure (such as the construction of a bridge). In this study, the period considers the influence of the Rio Negro Bridge (construction started in 2007) and the creation of the MMR (2007) as a way of including two important facts that may influence the projection of deforestation in the coming years.

The percentage difference in model validation between the observed map and the 2017 simulated map (see Table 4) for the deforestation class obtained in this study is similar to those found in other studies in the Amazon, which were 4.7% (Yanai et. al., 2012), 5.3% (Barni et al., 2015), 0.9% (Roriz et al., 2017), and 7.9% (Ramos et al., 2018). No other studies have modeled urban growth for the Amazon region to compare with our result. The percentage differences for the deforestation class and for the urban area class for the year 2017 may be mostly due to the differences in the transition rates of the municipalities used in the calibration and validation (see Supplementary Material, Table S-2 and Figure S-4). The greatest differences between the results in the observed and simulated maps were for the municipalities of Iranduba and Manacapuru, principally in relation to the expansion of the urban area. The simulated amounts of urban growth for Iranduba and Manacapuru are underestimated by -29.5 and -23.9%, respectively. These values represent the largest underestimations in absolute area found in the validation, which were 12.9 km^2 for Iranduba and 4.4 km^2 for Manacapuru. We chose to employ two different periods for calibration and validation to lessen the spurious effects of using the same transition rates in these two steps. Despite the differences for these two specific municipalities, the result of the validation for the study area was generally satisfactory. However, for the municipalities of Iranduba and Manacapuru, the results for 2100, especially in the case of urban growth, could be considered conservative.

The spatial model of deforestation and urban expansion used in the present study showed increased loss of forest cover due to the conversion of forest to deforestation and an increase in urban areas due to the advance of deforestation around these urban areas. The construction of the Rio Negro Bridge had an accelerating effect on the dynamics of land-use and cover change for

the municipalities that were connected to Manaus by the bridge. Our study incorporated the period of planning and the start of construction of the Rio Negro Bridge from 2007 to 2010 and captured the movement related to land speculation in the region. In the study by Ramos et al. (2018), the scenario simulated with the bridge considered the period from 2008 to 2010 and in our study, the period considered was from 2004 to 2010. Thus, our model considers the deforestation pattern related to the bridge effect. For the transition from deforestation to an urban area, the MMR municipalities showed similar urban growth rates, with the exception of the municipality of Manaus (see Supplementary Material, Figure S-3d).

The Rio Negro Bridge, inaugurated in 2011, and the good condition of the initial stretch of Highway BR-319 located in the municipalities of Careiro da Várzea and Careiro, demonstrated the influence of road access in increasing deforestation and, subsequently, urban growth. This effect of road access on deforestation has also been observed in other studies in the Amazon, including Dickinson (1989), Soares-Filho et al. (2004), Fearnside (2006), Fearnside et al. (2009), Yanai et al. (2012), Barber et al. (2014), Barni et al. (2015), and Ramos et al. (2018). Another important aspect is the effect of protected areas in preventing deforestation, contributing to the conservation of the forest. Novo Airão would have the smallest area deforested by the end of the century (Figure 8, see Supplementary Material, Figure S-1) because this municipality has a vast area of forest occupied by conservation units and is also far from the main highways (BR-174 and BR-319) (Figure 1). Yanai et al. (2012) showed how protected areas are important for curbing deforestation and the emergence of secondary roads, although protected do not entirely prevent deforestation (see Supplementary Material, Table S-4).

Our results also show urban expansion of the MMR near the already-urbanized areas, as was found in the State of São Paulo a study by Almeida et al. (2008). These authors simulated changes in intra-urban land use in a medium-sized city and showed that new residential and industrial subdivisions tend to appear around areas where these types of subdivisions already exist and in areas with good accessibility and/or that are near the main roads. Service corridors usually run along major roads and close to larger residential and commercial areas, and areas for subdivisions follow the same growth logic as industrial zones.

Despite its small urban area, the municipality of Careiro da Várzea has a high percentage of urban growth at the end of the century (see Figure 9). Although the municipality of Manaus had the highest rate of urban growth in the calibration period (2004-2010), in the validation period (2012-2017), and in the entire period analyzed (2004-2017) – 1% per year (Supplementary Material, Table S-2) and had the largest urban area at the end of the century (1508 km^2) – Manaus demonstrates the lowest urban growth during the simulation (503.3%). This result may be because the municipality of Manaus contains extensive conservation units and special areas (see Figures 1 and 3) that inhibit deforestation and consequently urban growth. This reinforces the importance of protected areas in forest conservation (Yanai et al., 2012). In addition, Manaus has a more consolidated urbanization process, while the other the MMR municipalities are in the initial process of expanding their urban area.

The influence of the road system on the growth of deforestation in the MMR is obvious. For example, the municipality of Presidente Figueiredo has extensive conservation areas (see Figure 1) and the second lowest rate of deforestation transition (Supplementary Material, Table

S-2), but the simulation showed extensive deforested by 2100 as compared to the area deforested by 2017. Highway BR-174, which connects Manaus with the State of Roraima, passes through a large part of this municipality. Presidente Figueiredo is also crossed by Highway AM-240. The southeastern portion of the MMR undergoes a greater expansion of deforestation (see Figure 9a and Supplementary Material, Figure S-2), which can be explained by the conditions of the highways in the study perimeter (BR-174 and AM-010).

The urban growth of the MMR seems to be strongly associated with pre-existing urban areas as well as with accessible transport routes, as presented by Almeida et al. (2008). The influence of the AM-070 and the Rio Negro Bridge for the expansion of the urban area of Iranduba and Manacapuru stand out. The municipalities interconnected by Highways BR-174, AM-010, and AM-070 had greater expansion of their urban areas than other municipalities (see Figure 9b). This confirms the influence of transport infrastructure on the increase in peri-urban deforestation (Ramos et al., 2018) and, consequently, on urban expansion.

Our results can be considered conservative, since there was still no paving of BR-319 and duplication of AM-010, which are expected to start in the coming years. This could accelerate the migration of deforestation to the Manaus area from the “arc of deforestation” (the heavily deforested strip along the southern and eastern edges of the Brazilian Amazon), as well as increase urban expansion due to population growth, such as the invasion of land for subdivisions on the outskirts of Manaus and neighboring municipalities.

Our results can assist public and private entities responsible for urban and environmental planning in the Amazon region and help in decision-making on urban planning and expansion of the road network. Future work could include socio-economic variables in the modeling, such as expansion of tax exemptions in the Manaus Free Trade Zone for the entire MMR (Laws No. 6951/2017 and No. 2633/2011), demographics, real estate speculation, per-capita income, the future market for agricultural commodities, and cattle ranching.

5. Conclusions

Deforestation projected to 2100 in the Manaus Metropolitan Region (MMR) is concentrated along the main and secondary roads. The simulated scenario indicates that, if deforestation rates persist, most the municipalities in the MMR would experience an increase of more than 100% in their deforested areas by the end of this century. Some MMR municipalities would have urban areas expand by over 500% by 2100. Thus, urbanization in the MMR may also represent a new “frontier” that will contribute to exacerbate the loss of Amazonian forests by increasing pressure for new deforested areas.

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Supplementary Material

Amazon deforestation and urban expansion: simulating future growth in the Manaus Metropolitan Region, Brazil

Appendix 1. The PRODES project

The PRODES project performs satellite monitoring of deforestation in the Brazilian Legal Amazon region by identifying and delimiting deforested areas where there has been complete removal of forest cover (i.e., clear cutting) of at least 6.25 ha. The TerraClass project classifies deforestation into different types of land use/cover, based on the PRODES project, with data for the years 2004, 2008, 2010, 2012, and 2014 (INPE, 2017).

Appendix 2. Attractiveness and friction maps.

Attractiveness and friction maps assist in allocating new secondary roads each year of the simulation. These maps are used in the road-builder module. The road-builder module identifies the lowest-cost route for the construction of new roads, taking into account the level of attractiveness and friction of the simulated region (Soares-Filho et al., 2009). The attractiveness map was built based on a multicriteria analysis assigning weights to areas considered attractive for human activities, such as those close to existing roads, previously deforested areas, and urban areas. Similarly, the combination of protected areas (conservation units, Indigenous lands, Quilombola lands) and special areas such as the Adolpho Ducke Forest Reserve (ADR) and military areas was used to create the friction map, which represents the relative cost of road construction.

Appendix 3. The Module Change Matrix function

The Module Change Matrix function concerns the proportion of status changes in the expander function performed at each transition. Since the cell size is equal to 1 hectare, the simulated patches will have a mean of 5 ha with a range of zero to 10 ha for the transition from forest to deforestation. For the transition from deforestation to urban area, the simulated patches will have a mean of 5 ha without variation in their size. Finally, the Patch Isometry parameter defines the shape of the simulated patches, ranging from 0 to 2. The closer to 2 the more isometric the simulated patches will be (Soares-Filho et al., 2009).

Table S-1. Similarities achieved in Dinamica EGO models in the Amazon.

Resolution	**Similarity (%)**	**Window (pixel) with 50% similarity**	**Reference**
100 m	57	7 × 7	This Study
250 m	55	7 × 7	Barni, 2015
250 m	57	5 × 5	Yanai et al., 2012
120 m	50	11 × 11	Ramos et al., 2018
100 m	59		Teixeira and Soares-Filho., 2009
100 m	50	11 × 11	Maeda et al., 2011
30 m	54	5 × 5	Roriz et al., 2017

Table S-2. Values of the initial net rates for deforestation and urban expansion of the MMR for different time intervals between 2004 and 2017.

Forest-Deforestation transition rates per year

Municipality	2004-2010	2010-2017	2012-2017	2004-2014	2014-2017	2004-2017
Autazes	0.00956	0.00574	0.00565	0.00875	0.00336	0.00751
Careiro	0.00600	0.00313	0.00303	0.00559	0.00070	0.00446
Careiro da Várzea	0.02508	0.01629	0.01793	0.02314	0.01105	0.02036
Iranduba	0.00997	0.00744	0.00967	0.01062	0.00255	0.00880
Itacoatiara	0.01149	0.00628	0.00728	0.01057	0.00244	0.00870
Itapiranga	0.00162	0.00106	0.00073	0.00165	0.00022	0.00133
Manacapuru	0.00573	0.00360	0.00433	0.00556	0.00139	0.00460
Manaquiri	0.00287	0.00152	0.00155	0.00260	0.00062	0.00214
Manaus	0.00391	0.00288	0.00359	0.00444	0.00038	0.00346
Novo Airão	0.00015	0.00012	0.00015	0.00016	0.00004	0.00013
Presidente Figueiredo	0.00149	0.00126	0.00120	0.00163	0.00053	0.00137
Rio Preto da Eva	0.00383	0.00282	0.00347	0.00407	0.00086	0.00331
Silves	0.00431	0.00237	0.00227	0.00411	0.00045	0.00326

Deforestation-Urban transition rates per year

Municipality	2004-2010	2010-2017	2012-2017	2004-2014	2014-2017	2004-2017
Autazes	0.00024	0.00024	0.00024	0.00024	0.00030	0.00026
Careiro	0.00038	0.00024	0.00033	0.00033	0.00024	0.00032
Careiro da Várzea	0.00002	0.00007	0.00008	0.00006	0.00005	0.00005
Iranduba	0.00428	0.00786	0.00948	0.00672	0.00644	0.00690
Itacoatiara	0.00063	0.00039	0.00051	0.00051	0.00052	0.00054
Itapiranga	0.00163	0.00187	0.00220	0.00207	0.00141	0.00206
Manacapuru	0.00083	0.00150	0.00186	0.00128	0.00135	0.00136
Manaquiri	0.00018	0.00022	0.00030	0.00020	0.00024	0.00021
Manaus	0.01073	0.00998	0.01019	0.01155	0.01015	0.01124
Novo Airão	0.00101	0.00213	0.00146	0.00185	0.00154	0.00195
Presidente Figueiredo	0.00140	0.00138	0.00115	0.00150	0.00157	0.00157
Rio Preto da Eva	0.00314	0.00199	0.00262	0.00275	0.00269	0.00267
Silves	0.00032	0.00009	0.00012	0.00022	0.00015	0.00019

Table S-3. Model configuration for the land-use/cover simulation of the MMR. The transitions considered are Forest to Deforestation and Deforestation to Urban Area.

Transition	Calibration period	Validation period	Module Change Matrix	Expander (Patcher)			Comparison year observed vs. simulated map
				Mean Patch Size (Ha)	Patch Size Variance (Ha)	Patch Isometry	
Forest to Deforestation	2004-2010	2012-2017	0.2	5 (5)	10 (0)	1.5 (1.5)	2017
Deforestation to Urban Area	2004-2010	2012-2017	0.9	5 (5)	0 (0)	1.5 (1.5)	
Null model (coefficient values of zero for the weights-of-evidence)							
Forest to Deforestation	2004-2010	2012-2017	0.2	5 (5)	10 (0)	1.5 (1.5)	2017
Deforestation to Urban Area	2004-2010	2012-2017	0.9	5 (5)	0 (0)	1.5 (1.5)	

Table S-4. Deforested area and urban area of protection units, Indigenous lands, and special areas (parks and military areas) for the period from 2020 to 2100 for the MMR.

Deforestation Area (km²)

Regions	2020	2030	2040	2050	2060	2070	2080	2090	2100
Integral Protection	34.9	419.1	46.4	50.8	57.2	66.7	77.6	92.0	115.4
Sustainable Use	2,030.1	2,534.8	3,002.9	3,432.1	3,835.7	4,200.3	4,521.2	4,797.3	5,040.5
Indigenous Lands	373.9	474.8	581.0	676.0	776.8	881.9	998.0	1,121.3	1,230.5
Special Areas	1.1	1.8	2.5	4.3	6.3	8.3	10.8	13.6	16.0

Urban Area (km²)

Regions	2020	2030	2040	2050	2060	2070	2080	2090	2100
Integral Protection	0.6	0.6	0.6	0.7	0.7	0.7	0.8	0.8	0.9
Sustainable Use	142.9	206.0	283.5	384.9	504.6	642.7	799.7	980.6	1,186.6
Indigenous Lands	0.2	0.6	1.0	1.8	2.5	3.2	3.9	5.1	6.1
Special Areas	0.06	0.8	1.5	2.0	3.1	3.9	5.0	6.8	9.3

Figure S-1. Forest area rate in municipalities of the MMR from 2017 to 2100 and absolute values in km^2.

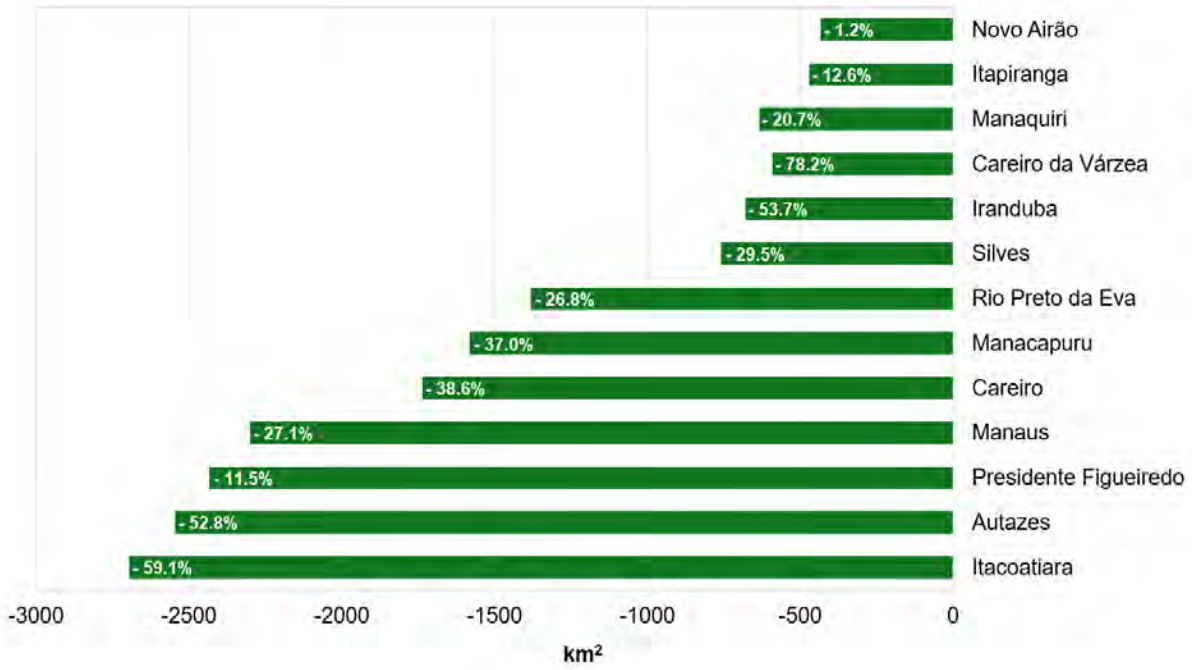


Figure S-2. Map of land use/cover in 2017 and expected change of land use/cover in 2100 for the MMR.

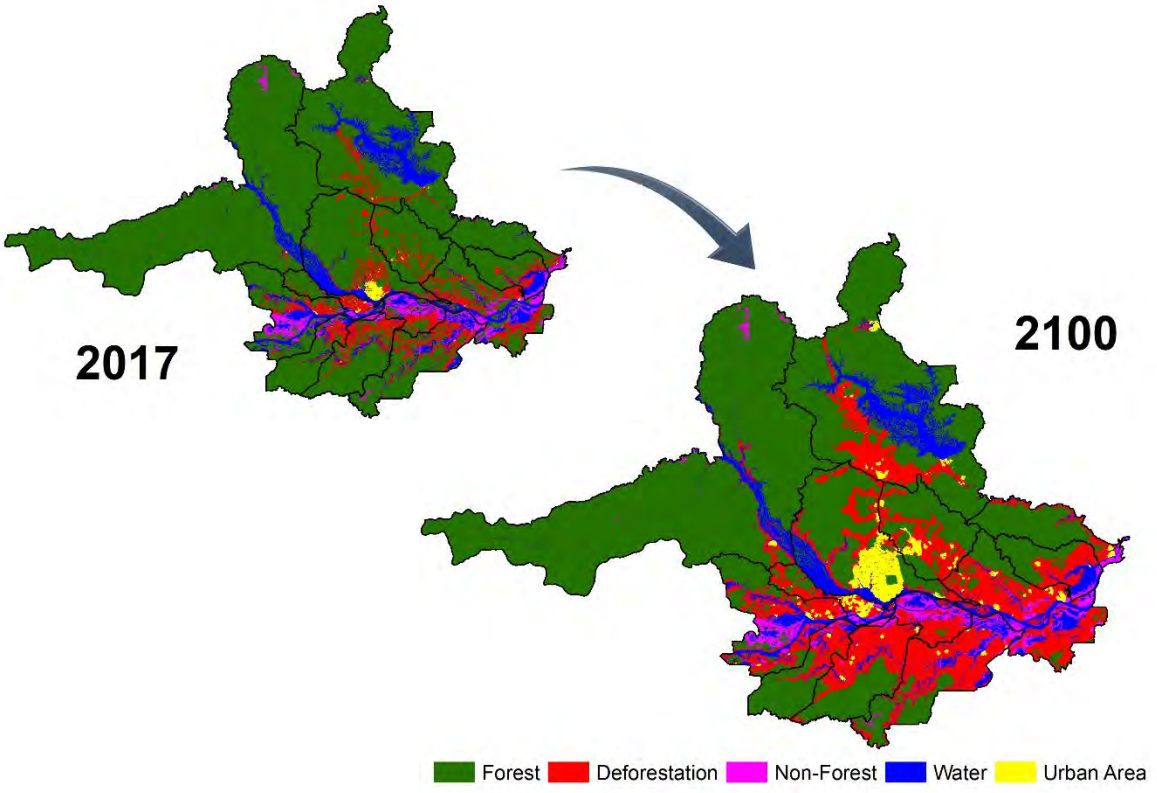


Figure S-3. Values of deforestation rates of increase (km^2 $year^{-1}$) for the Legal Amazon region (yellow bar), the state of Amazonas (blue bar), and the MMR municipalities for the period between 2004 and 2017. Sources: PRODES (2019a); PRODES (2019b); INPE (2017).

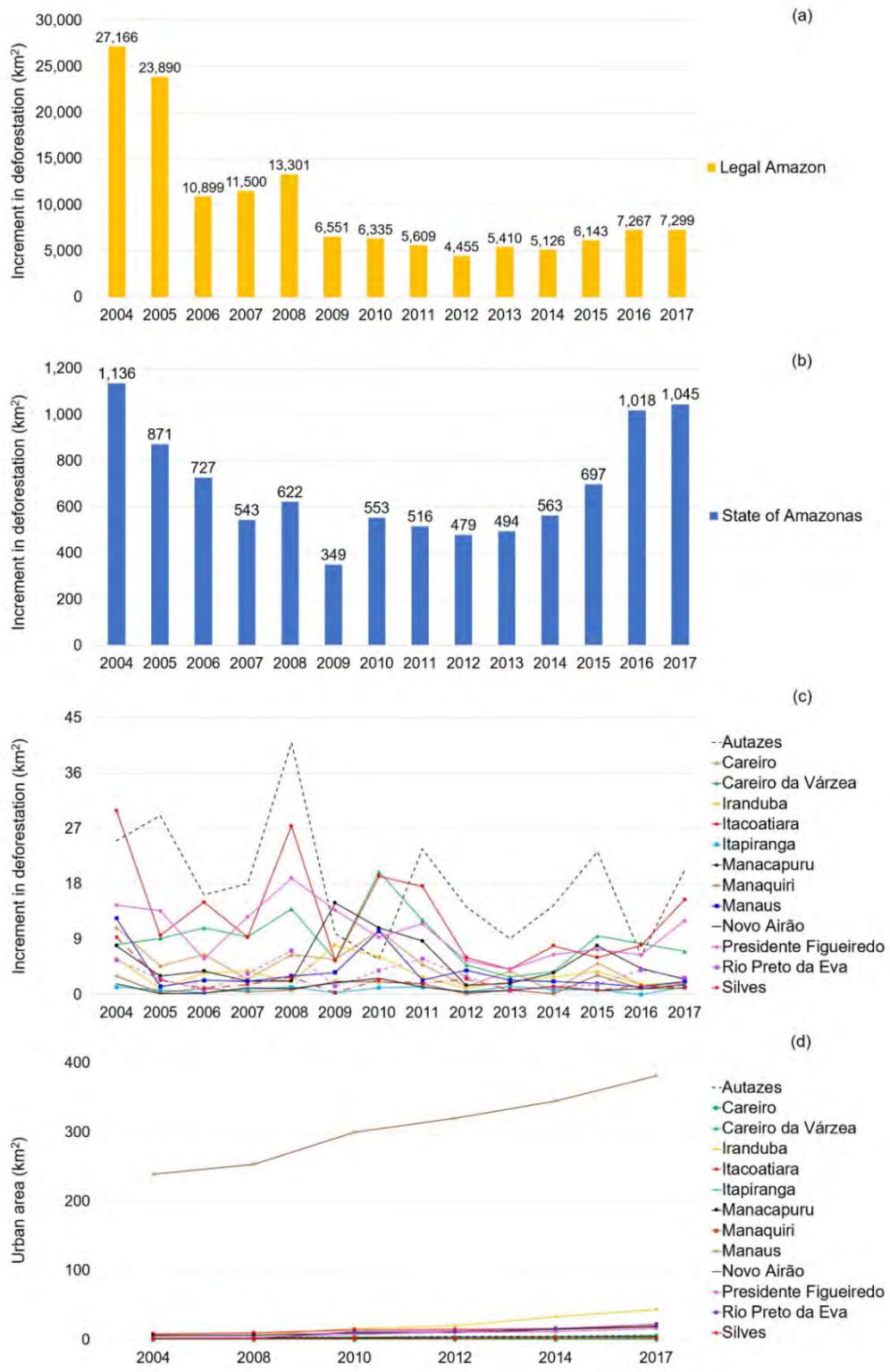
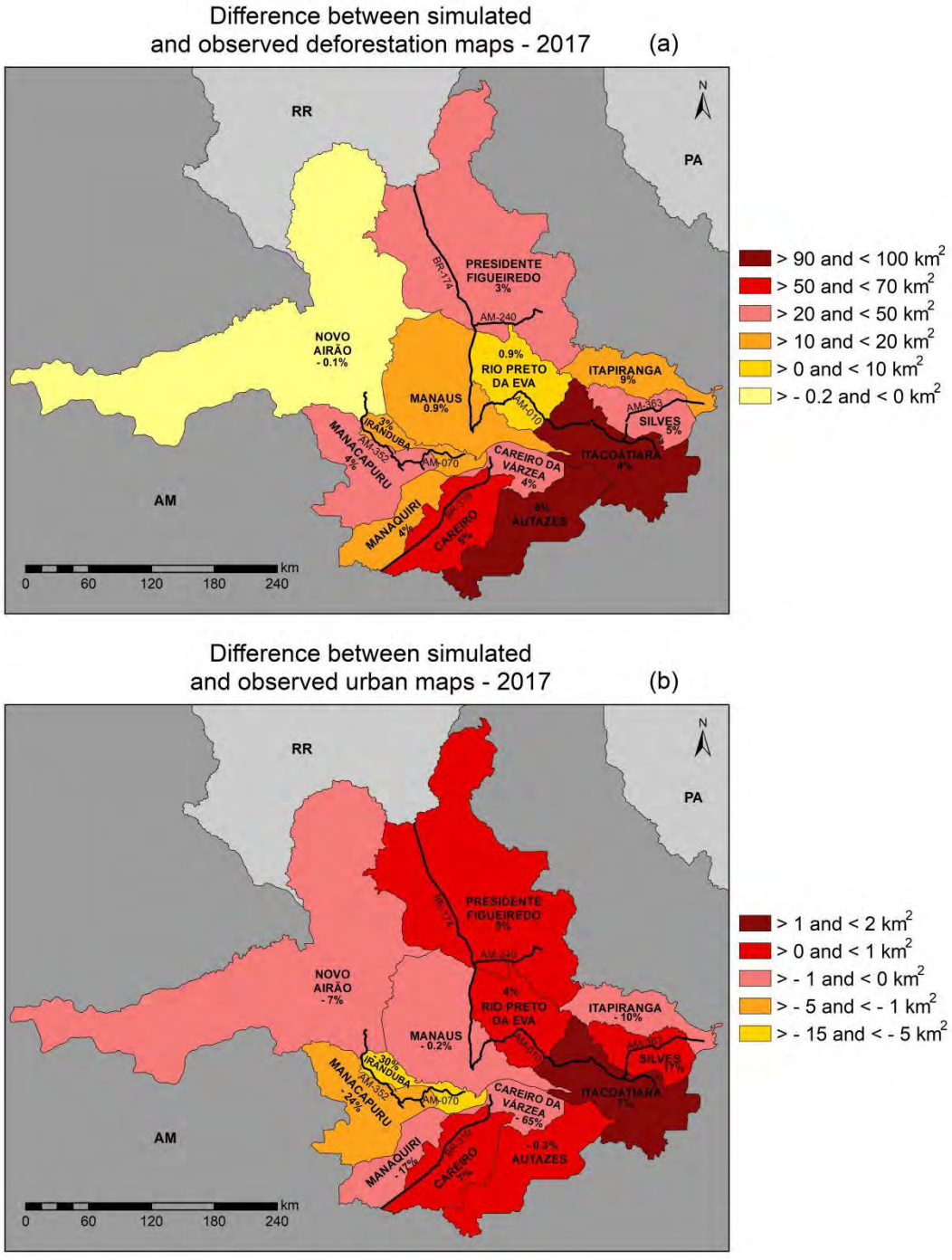


Figure S-4. Spatial distribution of the difference between deforestation areas and urban areas between the observed and simulated 2017 maps for the MMR.



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