

This file has been cleaned of potential threats.

If you confirm that the file is coming from a trusted source, you can send the following SHA-256 hash value to your admin for the original file.

393ceea13d56bd7d77968c1ee3152e3e9e4f9eb923ddfbf044af632a87c7e6e0

To view the reconstructed contents, please SCROLL DOWN to next page.

**The text that follows is a PREPRINT.
O texto que segue é um PREPRINT.**

Please cite as:

Favor citar como:

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

Copyright: Springer.

The original publication is available at:

A publicação original está disponível em:

<http://www.springerlink.com>

<https://doi.org/10.1007/s00267-018-1097-3>

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

1

2 1. ABSTRACT

3

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

21

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

23

24 **Highlights**

25

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

27

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

29

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

31

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

33

34 **1. Introduction**

35

36 Urbanization is rapidly progressing in the Amazon region. In 2010 the Brazilian
 37 Amazon had 71% of its population in urban areas (Brazil, IBGE 2016a), and urbanization
 38 has become a major environmental problem in the Amazon due to rapid migration and lack
 39 of infrastructure (Becker 2001). Amazon deforestation represents one of the world's great
 40 environmental problems, and understanding its multiple causes is a high research priority
 41 on a global scale. Urban growth has been one of the most powerful forces in worldwide
 42 landscape change in recent decades (Su et al. 2014; Wang and Qiu 2017), and this impact is
 43 expected to increase dramatically by 2030 (Forman and Wu 2016). Urban areas are
 44 expanding into the countryside, a phenomenon known as "peri-urbanization." Peri-urban

45 areas are characterized by having urban, rural and natural elements at different levels. The
46 landscape is not static, but rather changes over time (Allen 2003; Moreira et al. 2016).

47

48 Interaction between an urban area and its associated peri-urban area is determined
49 by factors such as population density, availability of roads, land use and territorial planning
50 (Tacoli 2003). Increased mobility can intensify income-generating activities by allowing
51 commuting between these areas; examples of these relations include interchange between
52 agricultural producers and urban markets and increasing real-estate speculation for
53 residential and recreational uses (e.g., Yu and Ng 2007). It is therefore expected that an
54 abrupt improvement of the transport network connecting an urban center to its surroundings
55 can cause major changes in land cover. Urban growth can be classified into three types:
56 “infilling” (increasing population density in the existing urban area), “edge-expansion”
57 (urbanization advancing from the edges of an existing urban area) and “outlying”
58 (emergence of new urban patches that are isolated from existing urban areas) (Shi et al.
59 2012). In the case of an outlying area being connected to an urban center by improving a
60 road network, the process becomes one of edge expansion and thus increases the potential
61 for the spread of urban areas.

62

63 Manaus (2016 population 2.1 million: Brazil, IBGE 2017) is located in central
64 Amazonia near the confluence of the Rio Negro and the Upper Amazon (Solimões) River.
65 The city has grown rapidly as a free-trade zone where factories assemble products from
66 imported components. The Rio Negro, one of the world’s largest rivers, has served as a
67 barrier blocking expansion of the city to the south. The Rio Negro Bridge, inaugurated on
68 24 October 2011, eliminated this barrier (Figure 1). The Rio Negro Bridge presents an
69 unusually clear case for assessing the peri-urbanization process. In most cases, peri-
70 urbanization spreads gradually in concentric circles as a city grows, thereby not providing
71 clear “before” and “after” periods. In the case studied here, however, the building of a
72 bridge suddenly opened the floodgates to peri-urban expansion from Amazonia’s largest
73 city.

74

75 [Fig._1_here]

76

77 Deforestation on the right bank of the Rio Negro can be expected to increase due to
78 factors such as the population growth of Manaus (Supplementary material, Figure S-1),
79 construction of a university center in the municipality of Iranduba, widening the AM-070
80 road, and expanding existing activities in brick and tile production, as well as the
81 announcement of plans for a variety of other projects (Moreira et al. 2009; Rodrigues et al.
82 2014; Sousa 2015). There is also a plan to rebuild Highway BR-319, a road that has been
83 abandoned since 1988 and, if reopened, would connect the Manaus area to Brazil’s
84 notorious “arc of deforestation” in southern Amazonia, thus facilitating migration and
85 increasing deforestation (Fearnside et al. 2009; Soares-Filho et al. 2006, Nepstad et al.
86 2011). Roads represent one of the main drivers of Amazonian deforestation (Fearnside
87 2017a,b; Kirby et al. 2005; Laurance et al. 2002; Souza Jr. et al. 2005), and 95% of the
88 deforestation in Brazilian Amazonia occurs within 5.5 km of a road (Barber et al. 2014).
89 Added to these factors, the urban zone of Manaus is compressed between the Tarumã-Açu
90 River, the Adolpho Ducke Forest Reserve and the Rio Negro (Supplementary material,
91 Figure S-2). The Rio Negro Bridge has raised demand for property on the right bank of the

92 river, increasing the value of urban land and fueling real-estate speculation (Sousa 2015).
93 Interest is no longer only focused on agricultural production, but the area still lacks many
94 urban attributes, leading to low population density and a lack of services and infrastructure
95 (Allen 2003).

96
97 The objective of this study was to evaluate the spatial dynamics of deforestation
98 resulting from an infrastructure project that connects an area of peri-urbanization to a major
99 city. This evaluation, which is based on the comparison of scenarios with and without the
100 bridge, allows assessment of how different patterns of land-cover change can occur through
101 "outlying" and "edge-expansion" dynamics in peri-urban areas. Our study simulates the
102 effect of the Rio Negro Bridge on deforestation in the municipalities of Iranduba,
103 Manacapuru and Novo Airão through 2030.

104
105 Deforestation in Amazonia has a wide variety of environmental impacts, including
106 site degradation through soil erosion and other processes, loss of biodiversity and loss of
107 the forest's functions in maintaining climatic stability by storing carbon and by recycling
108 water that supplies rainfall both in Amazonia and in other parts of Brazil and neighboring
109 countries (Fearnside 2017a,b). The gravity of these impacts makes advances in our ability
110 to model the deforestation consequences of different development decisions an important
111 priority not only for Amazonia but also for other parts of the world.

112 113 **2. Methods**

114 115 2.1. Study area

116
117 The municipalities of Iranduba (land area of 2214 km²), Manacapuru (7330 km²)
118 and Novo Airão (37,771 km²) are located in the Manaus Metropolitan Region, in Brazil's
119 state of Amazonas (Figure 1). The estimated 2016 populations of these municipalities were
120 46,703, 95,330 and 18,133 inhabitants, respectively (Brazil, IBGE 2016b). The
121 municipality of Novo Airão is bisected by the Rio Negro and Manacapuru is bisected by
122 the Upper Amazon (Solimões) River, while all of Iranduba is in the wedge of land between
123 these two great rivers (Figure 1). The study area is restricted to the area under direct
124 influence of the bridge, which corresponds to the wedge of land between the right bank of
125 the Rio Negro and the left bank of the Upper Amazon (Solimões). This area was bounded
126 by a 30-km buffer around the main roads: AM-070 and AM-352 (Figure 2A).

127
128 [Fig_2_here]

129
130 The main economic activity in the three municipalities is farming (temporary and
131 permanent), followed by pasture (Fernandes 2013). Land use is characterized as a mosaic
132 of occupations for family agriculture and livestock. In addition, these municipalities,
133 especially Novo Airão, have long had ecotourism as a major activity.

134
135 The study area was divided into "regions" (regionalized) according to road density
136 in the period from 2004 to 2014. The study area is extensive and has a variety of
137 peculiarities, making regionalization necessary in order to capture the different spatial
138 characteristics of deforestation (Figure 2A). The simulation was run individually for each

139 region of the study area. The density of roads provides a means of distinguishing the five
140 regions. First, a 1-km buffer was delimited around the great rivers. This buffer denominated
141 "River access" represents the influence of the main water bodies as transportation
142 connections to these areas. The remaining area was divided into regions according to road
143 densities calculated as the length of roads per unit area (km/km^2). Increase in roads in this
144 period differed among the regions, which were therefore ranked according to road density
145 as well as according to the increase in roads. Additionally, field observations were
146 undertaken for reconnaissance of the study area and to gain an understanding of changes in
147 land cover (Supplementary Material, Appendix 1).

148

149 2.2. The AGROECO Model

150

151 The methodological steps in the study are summarized diagrammatically in the
152 Supplementary Material (Figure S-3). We simulated deforestation from 2011 to 2030 under
153 "Bridge" and "No-bridge" scenarios using the AGROECO spatial model developed by
154 Fearnside et al. (2009), which is implemented in Dinamica-EGO software (Rodrigues et al.
155 2007; Soares-Filho et al. 2002, 2009). The model is based on cellular automata, which
156 represent the dynamics of a system as a grid. Each cell of an n -dimensional system of cells
157 will have its state updated in discrete steps based on a set of transition rules that are
158 specified in accord with a particular neighborhood (Soares-Filho et al. 2002, 2007).
159 Cellular-automata models are tools with great potential for understanding urban dynamics
160 because they integrate spatial and temporal dimensions of these dynamics (Santé et al.
161 2010). Spatial predictive models simulate the alteration of environmental attributes, thus
162 helping to understand the causal mechanisms and the dynamics of environmental systems
163 (Soares-Filho et al. 2007).

164

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

173

174 2.3. Input data for the spatial model

175

176 Ecosystem services, here represented by forests, have an essentially spatial nature,
177 thus requiring representation with maps (Swetnam et al. 2011). Maps of land cover from
178 2004 to 2010 were prepared for the study area from PRODES deforestation data (Brazil,
179 INPE 2018). PRODES is the Project for Monitoring the Brazilian Amazon Forest by
180 Satellite, through which the National Institute for Space Research (INPE) maps Brazil's
181 Amazonian deforestation annually. The minimum area of deforestation mapped by
182 PRODES is 6.25 ha. We used the UTM [Universal Transverse Mercator] map projection
183 with UTM Zone 20 S and Datum WGS [World Geodetic System] 1984. In the processes of
184 calibration and simulation the spatial resolution adopted was 120 m, and the data were in
185 raster format.

186
187 The set of variables used can be seen in the Table 1. The variables examined
188 represent a set of spatially determined social and biophysical factors. Some of the variables
189 used are static and do not change with every iteration. Distance to municipal seats is an
190 indicator of population and a proxy for local markets (Aguiar et al. 2007). Dynamic
191 variables were also used that are updated in each iteration of the model and are displayed in
192 the form of maps.

193
194 [Table_1_here]

195
196 Maps of “attractiveness” for roads and “friction” impeding road construction were
197 generated in the Dinamica-EGO software, as described by Soares-Filho et al. (2009). The
198 attractiveness map provides input to the calculation of target cells for building roads, and
199 the map is built based on characteristics of the area that act as attractions to human
200 activities such as proximity to existing roads and to previously cleared areas. Similarly, the
201 combination of maps for protected areas (conservation units and indigenous lands) was
202 used to create the friction map to identify the least-cost pathway to construct each new road
203 (see Supplementary Material, Appendix 2). The values adopted (following these
204 weightings) are presented in the Supplementary Material (Table S-1). Thus, the roads are
205 automatically placed in accordance with the level of attractiveness and the cost of
206 constructing a road.

207 208 2.4 Calibration

209 210 2.4.1 Periods used to calibrate the scenarios

211
212 The calibration phase is the stage when model parameters are fit to achieve the best
213 match between the simulated model and the PRODES deforestation data in the calibration
214 period for each scenario. The model was calibrated based on historical dynamics of
215 deforestation in the study area itself. The dates used in each scenario are summarized in
216 Table 2. The No-bridge scenario used rates of deforestation between 2004 and 2006, a
217 period when the bridge neither existed nor was under construction. The Bridge scenario
218 considered the deforestation rates from 2008 to 2010, since construction of the Rio Negro
219 Bridge began in December 2007 and land-cover dynamics changed significantly after that
220 event.

221
222 [Table_2_here]

223
224 The periods used are short (Supplementary Material, Appendix 3). However, data
225 from PRODES (Brazil’s official deforestation monitoring program) are available only
226 beginning in 2000. The deforestation rate was extremely high at the beginning of the 2000s
227 both for the study area and for surrounding municipalities. In Amazonia as a whole
228 deforestation dropped precipitously after 2004, but in the study area the major drop began
229 in 2002, and from 2004 to 2008 the rate declined slightly but remained relatively stable.
230 After 2008 there was a sequence of pulses of the deforestation rate (Supplementary
231 Material, Figure S-5). We therefore only used the years immediately prior to the start of
232 bridge construction as the reference for the "No-bridge" period. Because three years was

233 used for the reference period for the "No-bridge" scenario (2004-2006), a period of the
234 same three-year length (2008 -2010) was used as the reference period for the Bridge
235 scenario. The years after construction of the bridge began (i.e., 2008 onwards) show a
236 sequence of pulses in the deforestation rate, suggesting an intense dynamic in progress in
237 the region. This kind of accelerated deforestation activity in anticipation of implanting new
238 infrastructure has occurred repeatedly in the case of Amazonian highway projects, such as
239 the BR-163 (Santarém-Cuiabá) and BR-319 (Manaus-Porto Velho) highways (Fearnside
240 2007; Fearnside and Graça 2006). A recent effect of this kind was unleashed by
241 announcement of plans to remove protection from parts of some conservation units along
242 the BR-163 Highway, leading to a surge of invasion and deforestation in these areas
243 (Branford and Torres 2017).

244
245 The deforestation rate in each year is subject to many factors besides the existence
246 of a bridge, include major economic cycles, electoral cycles and variations in the effort
247 applied to enforcing environmental restrictions. Deforestation rates in Brazilian Amazonia
248 as a whole underwent a prolonged decline from 2004 to 2012 for a combination of reasons
249 (e.g., Fearnside 2017a,b). If the No-bridge scenario were to use the early 2000s as a
250 baseline, this scenario would be based on parameters for a period with a substantially
251 higher average deforestation rate than the baseline used for the Bridge scenario, thereby
252 artificially making the bridge appear to have a beneficial effect in slowing deforestation. On
253 the other hand, a spurious result would also occur if the No-bridge scenario were to use as a
254 baseline the three-year period when the bridge was under construction but not yet
255 completed (i.e., 2008-2010) because this period had an increased rate of deforestation due
256 to the rapid rise in real estate values and resulting land speculation. The year 2008 marks
257 the beginning of the influence of the bridge.

258

259 2.4.2 Weights of evidence

260

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

276

277 2.4.3 Deforestation rate

278

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

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

296

297

298 Where:

299 \mathbf{R} = Rate of deforestation (ha cleared per year)300 \mathbf{A}_{AFS} = Area of the agrarian forest surface (ha)301 \mathbf{P}_{AFS} = Deforestation proportion for the agrarian forest surface (proportion of remaining
 302 forest cleared per year)303 \mathbf{A}_{out} = Area outside of the agrarian forest surface (ha)304 \mathbf{P}_{out} = Deforestation proportion for the area outside of the agrarian forest surface (proportion
 305 of remaining forest cleared per year)

306

307 [Table_3_here]

308

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

312

313 Dinamica-EGO converts the deforestation simulated between two functions: the
 314 "Expander" and the "Patcher" (Soares-Filho et al. 2009). The Expander makes simulated
 315 deforestation occur as an enlargement of clearings that have already been initiated, while
 316 the Patcher creates new clearings, thereby initiating new deforestation foci in the landscape.
 317 Both functions have input parameters for adjusting the isometry, variance and average size

318 of patches of clearing (Soares-Filho et al. 2007). These parameters are set in the model
319 calibration phase for each scenario.

320

321 2.5. Validation

322

323 The validation step provides a measure of how well model results match
324 observations in the real world, and thus whether it is appropriate to proceed with the
325 analysis. To validate the amount of change, the numbers of cleared cells were compared
326 between the simulated and observed maps for the five regions in each scenario
327 (Supplementary Material, Table S-3). For the No-bridge scenario the simulated and
328 observed land-cover maps were for 2006, while for the Bridge scenario these maps were for
329 2010. Initially, there was a 7.9% validation error for deforestation in the study area as a
330 whole for each scenario. The transition-rate calculation uses the concept of "agrarian forest
331 surface," which highlights the importance of roads in making the forest accessible to human
332 activities, but several new roads have been built that have only recently been occupied. This
333 explains the 7.9% underestimation of the deforested area in the simulation in the first
334 validation. The underestimate meant that the representation of deforestation was
335 conservative; we therefore made a correction of the average annual net rate of deforestation
336 to attenuate this effect. These rates were updated (Supplementary Material, Table S-4)
337 based on the percentage error of the deforestation projection specific to each region
338 (Supplementary Material, Appendix 5). The No-bridge scenario yielded a -0.09% error and
339 the Bridge scenario a 0.32% error for the entire study area. Validation for each region after
340 the updating of rates was also acceptable in both scenarios (Supplementary Material, Table
341 S-3).

342

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

355

356 3. Results

357

358 3.1. Regionalization of the study area

359

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

363

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

371

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

377

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

384

385 Region D (Very low road density) is the region with the lowest road density, with
386 0.06 km roads/km². This region had the second-fastest growth in percentage terms.
387 However, since road density is still very low in absolute terms, the potential for expansion
388 of roads and deforestation within the simulation time frame is also lower as compared to
389 the other regions. The Very low road-density region includes the municipal seat of Novo
390 Airão, which has the smallest population of the three municipalities of the study area. Novo
391 Airão has large areas of forest and its economy is based on ecotourism. This is therefore an
392 area with potential for road expansion.

393

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

399

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

405

406 In 2010, the entire study area had a deforested area of 90,694 ha, with the “High,”
407 “Average,” “Low,” and “Very low” road-density regions and the “River access” region
408 having 31,423, 18,247, 8915, 2509 and 29,597 ha, respectively. These values are derived
409 from deforestation data available from PRODES based on 30-m resolution Landsat-TM
410 (Land Remote-Sensing Satellite-Thematic Mapper) imagery (Brazil, INPE 2018). The

411 historical sequence of annual deforestation rates is detailed in the Supplementary Material
412 (Appendix 6 and Figure S-9).

413

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

422

423 3.2. Simulation of deforestation for both scenarios

424

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

430

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

436

[Figs_3_ & _4_here]

438

439 Over the 2011-2030 period, deforestation in the Bridge scenario was 31,790 ha,
440 which represents 106% more than the No-bridge scenario (Figure 3). For the High road-
441 density, Average road-density, Low road-density, Very low road-density and River-access
442 regions the cumulative areas of deforestation in the period were 3944, 2445, 16,391, 3193
443 and 5816 ha, respectively (Figure 3). For this scenario, these values represent increases of
444 34%, 393%, 52% and 28%, respectively. Only the Average road-density region had more
445 deforestation in the No-bridge scenario than in the Bridge scenario, with 4% more
446 deforestation occurring in this region in the No-bridge scenario than in the Bridge scenario
447 in this period.

448

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

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

466

467 **4. Discussion**

468

469 4.1. Cumulative deforestation in simulated scenarios

470

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

483

484 Acceleration of urbanization with construction of the Rio Negro Bridge functioned
485 as a catalyst simulating deforestation. In the High road-density region, even with few areas
486 of remaining forest, deforestation spread considerably in the Bridge scenario (34% more
487 than No-bridge scenario). The Average road-density region is still in the process of
488 consolidating roads and the area had little variation in deforestation rate throughout the
489 historical period (Table S-5). This resulted in little difference in deforestation between the
490 simulated scenarios (4% more in the No-bridge scenario). The Low road-density region had
491 deforestation expanding from its roads and also had a large percentage of forests available.
492 This combination resulted in a large increase in deforestation (393%) in the Bridge
493 scenario. The Very low road-density region had a 52% increase in the total area deforested
494 in the Bridge scenario as compared to the No-bridge scenario. Finally, the River-access
495 region had the greatest deforestation in the Bridge scenario (28%). This region is permeable
496 by definition because river transport is part of the culture and history of the Amazon, and
497 rivers are still an important means of transportation (Kuwahara et al. 2012; Sant'Anna
498 1998). What is observed in the results is that the areas that are most vulnerable to
499 deforestation are not those immediately next to the large urban center in this case. The most
500 vulnerable areas are those that result from the combination of ample available forest and an
501 expanding road network (Low road-density and Very low road-density regions). The peri-
502 urban areas feature multi-functionalities and diverse interests, and the occupation of land
503 extends beyond the strictly urban areas. The increased accessibility of Manaus to

504 municipalities on the right bank of the Rio Negro confirms the importance of transport
505 infrastructure in increasing peri-urban deforestation.

506

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

523

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

531

532 4.2. Other influences on future deforestation

533

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

544

545 The deforestation trend in the Bridge scenario offers a blend of the regional trend of
546 deforestation in rural areas and a tendency to increase due to peri-urban expansion around
547 Manaus. The simulation result for deforestation up to 2030 in the Bridge scenario is
548 therefore likely to represent an underestimate due to the conditions that prevailed during the
549 calibration period we used (2008-2010); deforestation in Brazilian Amazonia as a whole
550 trended upwards from 2012 to 2017. In addition, these results do not consider the changes

551 likely to occur with the planned reconstruction of Highway BR-319, which can be expected
552 to increase migration to this area (Fearnside and Graça 2006). Additionally, demand for
553 housing, food production, and other land uses will continue to increase if the trend in
554 population growth remains as in recent years (Brazil, IBGE 2015). The Rio Negro Bridge
555 allows production in the affected area to be restructured with the support of government
556 development policy; this is similar to previous development projects in Amazonia, which
557 have generally not improved the living conditions of residents where the projects are
558 installed (Sousa 2011).

559

560 4.3. New frontiers of deforestation versus conservation units

561

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

569

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

582

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

592

593 4.4. Considerations of unregulated occupation and their implications for deforestation, 594 and modeling in the context of peri-urban expansion

595

596 In the Bridge scenario there is also a new process of deforestation due to peri-
597 urbanization. The largest simulated percentage increases in deforested areas occurred in the

598 regions with “Low” and “Very low” road density. These are the regions that offer the
599 largest areas of available forest and their road networks have expanded in recent years, thus
600 making them more susceptible to new occupations. Added to this attraction is the push
601 from increasing land prices in the city of Manaus, including land for industry (Sá et al.
602 2010). Increased interest in peri-urban areas often results from growing competition for
603 available areas and the consequent high cost of construction in city centers (Shi et al. 2012).
604 Real-estate speculation is one of the most prominent economic activities on the right bank
605 of the Rio Negro and has environmental and social implications leading to more clearing
606 along roads and around the urban areas of Iranduba and Manacapuru (Sousa 2015). In
607 many of the side roads we visited there were signboards, fences, stakes and other markings
608 for subdividing land into residential lots. At some locations houses were being built and
609 electricity, satellite dishes and telephone lines were already present. However, in many
610 houses we could not find anyone. Other properties only had either a caretaker or hired
611 workers preparing land or building houses. Many of these houses are used only for
612 recreation on the weekends. There are many properties along the smaller roads with "for
613 sale" signs, including roads that still have no electricity. Proximity of a major metropolis to
614 a rural area can speed deforestation, since large owners often live in urban centers, meaning
615 that the financial resources for the deforestation are also close by (Fearnside 2008). The
616 prior existence of residences in a given area is often an important driver to promote
617 development of new peri-urban dwellings (e.g., Liu and Robinson 2016); this increases the
618 probability of land-cover change in these newly opened areas.

619

620 Lack and insecurity of housing are major factors in environmental degradation in
621 Manaus and other large cities in Brazil’s northern region (COHRE 2006). Intense and
622 disorderly occupation resulting from invasions by the low-income population has removed
623 primary forest in the urban area of Manaus (GEO-Cidades 2002). With the bridge this
624 dynamic can be expected to spread to the other side of the river, where there is no effective
625 environmental control policy. Land tenure is still fragile in rural portions of the study area
626 (Rodrigues et al. 2014; Sousa 2015), and legal measures for environmental protection
627 cannot be taken until the status of the land is defined (Sparovek et al. 2012). Other
628 problems associated with these occupations include pollution of soils, rivers and ground
629 water, loss of biodiversity and reduction of the carbon stock (e.g., Aguilar and Santos
630 2011). If effective measures for spatial planning are not taken, it is likely that the number of
631 illegal occupations will increase on the right bank of the Rio Negro.

632

633 Although Brazilian Amazonia had a deforestation rate of 4571 km²/year in 2012, the
634 lowest since 1988 when official monitoring began, the rate has trended upward since then,
635 reaching 6947 km²/year in 2017 (Brazil, INPE 2018). Increased deforestation can be
636 expected due to the basic drivers of the process having either grown or remained
637 unchanged, including the profitability of agriculture, road-construction plans and
638 continuing increase in population and investment in the region (Fearnside 2015). Large
639 cities in Brazil’s northern region are undergoing disorderly urbanization and they lack
640 housing and urban planning. The Brazilian government has been impervious to the appeals
641 and recommendations of the scientific community, and a series of recent harmful policies
642 threatens ecosystem services and biodiversity in Brazil (Azevedo-Santos et al. 2017;
643 Fearnside 2016, 2018). Government institutions involved in the conservation of this area
644 should pay special attention to changes in land cover in the area along the AM-352 road

645 and in the western portion of the municipality of Iranduba. These are areas that have great
646 potential for deforestation.

647

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

657

658 **5. Conclusions**

659

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

673

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

691

692 **Acknowledgments**

693

694 Funding was provided by Conselho Nacional do Desenvolvimento Científico e
 695 Tecnológico (CNPq: Proc 304020/2010-9; 311103/2015-4; 573810/2008-7), Fundação de
 696 Amparo à Pesquisa do Estado do Amazonas (FAPEAM: Proc 708565), Programa de
 697 Capacitação Institucional, Ministério de Ciência, Tecnologia e Comunicação (MCTIC
 698 Proc: 313157/2015-4), and Instituto Nacional de Pesquisas da Amazônia (INPA:
 699 15,125.PRJ). This article is a contribution of the Brazilian Research Network on Global
 700 Climate Change, FINEP/ Rede CLIMA Grant Number 01.13.0353-00.

701

702 **Conflicts of interest**

703

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

706

707 **References**

708

- 709 Aguiar APD, Câmara G., Escada MIS (2007) Spatial statistical analysis of land-use
 710 determinants in the Brazilian Amazonia: Exploring intra-regional heterogeneity.
 711 *Ecol Modelling* 209:169-188. <https://doi.org/10.1016/j.ecolmodel.2007.06.019>
- 712 Aguilar AG, Santos C (2011) Informal settlements' needs and environmental conservation
 713 in Mexico City: An unsolved challenge for land-use policy. *Land Use Pol* 28:649-
 714 662. <https://doi.org/10.1016/j.landusepol.2010.11.002>
- 715 Allen A (2003) Environmental planning and management of the peri-urban interface:
 716 Perspectives on an emerging field. *Environ and Urbaniz* 15(1):135-148.
 717 <https://doi.org/10.1177/095624780301500103>
- 718 Azevedo-Santos VM, Fearnside PM, Oliveira CS, Padiá AA, Pelicice FM, Lima Jr DP,
 719 Simberloff D, Lovejoy TE, Magalhães ALB, Orsi ML, Agostinho AA, Esteves FA,
 720 Pompeu PS, Laurance WF, Petrer Jr M, Mormul RP, Vitule JRS (2017) Removing
 721 the abyss between conservation science and policy decisions in Brazil, *Biodivers*
 722 *Conserv* 26:1745–1752. <https://doi.org/10.1007/s10531-017-1316-x>
- 723 Barber CP, Cochrane MA, Souza Jr CM, Laurance WF (2014) Roads, deforestation, and
 724 the mitigating effect of protected areas in the Amazon. *Biol Conserv* 177:203-209.
 725 <https://doi.org/10.1016/j.biocon.2014.07.004>
- 726 Becker BK (2001) Revisão das políticas de ocupação da Amazônia: É possível identificar
 727 modelos para projetar cenários? *Parcerias Estratégicas* 12:135-159.
 728 http://www.cgee.org.br/arquivos/pe_12.pdf
- 729 Bonham-Carter GF, Agterberg FP, Wright DF (1989) Weights of evidence modeling: a
 730 new approach to mapping mineral potential. In: Agterberg FP, Bonham-Carter GF
 731 (eds) *Statistical Applications in Earth Sciences*. Geological Survey of Canada,
 732 Ottawa, Ontario, Canada. pp 171-183
- 733 Branford S, Torres M (2017) Amazon land speculators poised to gain control of vast public
 734 lands. *Mongabay*, 27 March 2017. <https://news.mongabay.com/2017/03/amazon-land-speculators-poised-to-gain-control-of-vast-public-lands/> Accessed: 13 April
 735 2018
- 737 Brazil, AGU (2009) Termo de Conciliação. Controvérsia jurídica decorrente da existência
 738 da ação civil pública nº 2008.32.00.006041-6, versando acerca da edificação da

- 739 Ponte sobre o Rio Negro, no Estado do Amazonas. [Conciliation Agreement. Legal
740 dispute arising from the existence of civil suit No. 2008.32.00.006041-6, with
741 reference to the building of the bridge over the Rio Negro in Amazonas State].
742 Advocacia Geral da União (AGU), Brasília, DF, Brazil.
743 <http://agu.gov.br/page/download/index/id/600533> Accessed: 17 July 2015
- 744 Brazil, EMBRAPA (2005) Brasil em Relevô. Empresa Brasileira de Pesquisa Agropecuária
745 (EMBRAPA), Brasília, DF, Brazil.
746 <http://www.relevobr.cnpm.embrapa.br/download/am/am.htm>. Accessed: 3 May
747 2015
- 748 Brazil, FUNAI (2016) Terras indígenas - Geoprocessamento. Fundação Nacional do Índio
749 (FUNAI), Brasília, DF, Brazil. [http://www.funai.gov.br/index.php/indios-no-](http://www.funai.gov.br/index.php/indios-no-brasil/terras-indigenas)
750 [brasil/terras-indigenas](http://www.funai.gov.br/index.php/indios-no-brasil/terras-indigenas). Accessed: 23 February 2016
- 751 Brazil, IBGE (2007) Banco de dados – Geociências. Instituto Brasileiro de Geografia e
752 Estatística (IBGE), Rio de Janeiro, RJ, Brazil.
753 http://www.ibge.gov.br/servidor_arquivos_geo Accessed: 21 January 2008
- 754 Brazil, IBGE (2008) Cidades do Brasil – Pontos. Instituto Brasileiro de Geografia e
755 Estatística (IBGE). Laboratório de Cartografia da Universidade Federal de Santa
756 Maria, Santa Maria, RS, Brazil.
757 [http://coral.ufsm.br/cartografia/index.php?option=com_content&view=article&id=2](http://coral.ufsm.br/cartografia/index.php?option=com_content&view=article&id=20&Itemid=28)
758 [0&Itemid=28](http://coral.ufsm.br/cartografia/index.php?option=com_content&view=article&id=20&Itemid=28) Accessed: 5 May 2015
- 759 Brazil, IBGE (2015) Estimativas de População. Instituto Brasileiro de Geografia e
760 Estatística (IBGE), Rio de Janeiro, RJ, Brazil.
761 [http://www.ibge.gov.br/home/estatistica/populacao/estimativa2014/estimativa_tcu.s](http://www.ibge.gov.br/home/estatistica/populacao/estimativa2014/estimativa_tcu.shtm)
762 [htm](http://www.ibge.gov.br/home/estatistica/populacao/estimativa2014/estimativa_tcu.shtm) Accessed: 19 May 2015
- 763 Brazil, IBGE (2016a) Sinopse do Censo demográfico 2010. Instituto Brasileiro de
764 Geografia e Estatística (IBGE), Rio de Janeiro, RJ, Brazil.
765 <http://www.censo2010.ibge.gov.br/sinopse/index.php?dados=8> Accessed: 21
766 September 2016
- 767 Brazil, IBGE (2016b) Cidades. Instituto Brasileiro de Geografia e Estatística (IBGE), Rio
768 de Janeiro, RJ, Brazil.
769 <http://www.cidades.ibge.gov.br/xtras/uf.php?lang=&coduf=13&search=amazonas>
770 Accessed: 1 September 2016
- 771 Brazil, IBGE (2017) Cidades, Manaus. Instituto Brasileiro de Geografia e Estatística
772 (IBGE), Rio de Janeiro, RJ,
773 Brazil. [http://www.cidades.ibge.gov.br/painel/populacao.php?lang=&codmun=1302](http://www.cidades.ibge.gov.br/painel/populacao.php?lang=&codmun=130260&search=amazonas|manaus|infogr%EFicos:-evolu%E7%E3o-populacional-e-pir%E2mide-et%EFria)
774 [60&search=amazonas|manaus|infogr%EFicos:-evolu%E7%E3o-populacional-e-](http://www.cidades.ibge.gov.br/painel/populacao.php?lang=&codmun=130260&search=amazonas|manaus|infogr%EFicos:-evolu%E7%E3o-populacional-e-pir%E2mide-et%EFria)
775 [pir%E2mide-et%EFria](http://www.cidades.ibge.gov.br/painel/populacao.php?lang=&codmun=130260&search=amazonas|manaus|infogr%EFicos:-evolu%E7%E3o-populacional-e-pir%E2mide-et%EFria) Accessed: 22 April 2017
- 776 Brazil, INCRA (2014) Acervo fundiário. Instituto Nacional de Colonização e Reforma
777 Agrária (INCRA), Brasília, DF, Brazil. <http://acervofundiario.incra.gov.br>.
778 Accessed 22 September 2014
- 779 Brazil, INPE (2018) Projeto PRODES - Monitoramento da Floresta Amazônica Brasileira
780 por Satélite. Instituto Nacional de Pesquisas Espaciais (INPE), São José dos
781 Campos, São Paulo, Brazil.
782 <http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes> Accessed: 24
783 June 2018

- 784 Brazil, MMA (2015) Mapas – Unidades de Conservação. Ministério do Meio Ambiente
785 (MMA), Cadastro Nacional de Unidades de Conservação (CNUC), Brasília, DF,
786 Brazil. <http://mapas.mma.gov.br/i3geo/datadownload.htm> Accessed: 4 May 2015
- 787 Brazil, SIPAM (2007) Mapa de Vegetação. Sistema de Proteção da Amazônia (SIPAM),
788 Manaus, Amazonas, Brazil.
789 http://www.dpi.inpe.br/amb_data/Shapefiles/Vegeta%C3%A7%C3%A3o%20SIPAM/
790 M/ Accessed: 4 May 2015
- 791 COHRE (2006) Conflitos urbano-ambientais em capitais amazônicas: Boa Vista, Belém,
792 Macapá e Manaus [Urban-environmental conflicts in the Amazonian capitals: Boa
793 Vista, Belém, Macapá and Manaus]. Centro pelo Direito à Moradia contra Despejos
794 (COHRE), Porto Alegre, RS, Brazil. 92 pp
795 <http://www.ceap.br/material/MAT23022012190943.pdf>. Accessed: 23 July 2015
- 796 FAS (2010) FAS e ACS Rio Negro discutem investimentos da Bolsa Floresta Renda e
797 Social. [FAS and ACS Rio Negro discuss investments in the Forest Stipend income
798 and social aspects]. Fundação Amazonas Sustentável (FAS), Manaus, Amazonas,
799 Brazil. [http://fas-amazonas.org/2010/06/fas-e-acrs-rio-negro-discutem-](http://fas-amazonas.org/2010/06/fas-e-acrs-rio-negro-discutem-investimentos-do-bolsa-floresta-renda-e-social/?lang=pt)
800 [investimentos-do-bolsa-floresta-renda-e-social/?lang=pt](http://fas-amazonas.org/2010/06/fas-e-acrs-rio-negro-discutem-investimentos-do-bolsa-floresta-renda-e-social/?lang=pt) Accessed: 23 July 2015
- 801 Fearnside PM (2007) Brazil's Cuiabá-Santarém (BR-163) Highway: The environmental
802 cost of paving a soybean corridor through the Amazon. *Environ Manage* 39(5):601-
803 614. <https://doi.org/10.1007/s00267-006-0149-2>
- 804 Fearnside PM (2008) Will urbanization cause deforested areas to be abandoned in Brazilian
805 Amazonia? *Environ Conserv* 35(3):197-199.
806 <https://doi.org/10.1017/S0376892908004906>
- 807 Fearnside PM (2015) Deforestation soars in the Amazon. *Nature* 521:423.
808 <https://doi.org/10.1038/521423b>
- 809 Fearnside PM (2016) Brazilian politics threaten environmental policies. *Science* 353:746-
810 748. <https://doi.org/10.1126/science.aag0254>
- 811 Fearnside PM (2017a) Deforestation in Brazilian Amazonia. In Wohl E (Ed), Oxford
812 Bibliographies in Environmental Science. Oxford University Press, New York,
813 USA. <https://doi.org/10.1093/obo/9780199363445-0064>
- 814 Fearnside PM (2017b) Deforestation of the Brazilian Amazon. In Shugart H (Ed), Oxford
815 Research Encyclopedia of Environmental Science. Oxford University Press, New
816 York, USA. <https://doi.org/10.1093/acrefore/9780199389414.013.102>
- 817 Fearnside PM (2018) Challenges for sustainable development in Brazilian Amazonia.
818 *Sustainable Devel* 26:141-149. <https://doi.org/10.1002/sd.1725>
- 819 Fearnside PM, Graça PMLA (2006) BR-319: Brazil's Manaus - Porto Velho Highway and
820 the potential impact of linking the arc of deforestation to central Amazonia. *Environ*
821 *Manage* 38(5):705-716. <https://doi.org/10.1007/s00267-005-0295-y>
- 822 Fearnside PM, Graça PMLA, Keizer EWH, Maldonado FD, Barbosa RI, Nogueira EM
823 (2009) Modelagem de desmatamento e emissões de gases de efeito estufa na região
824 sob influência da Rodovia Manaus-Porto Velho (BR-319) [Modeling deforestation
825 and greenhouse-gas emissions in the region under influence of the Manaus-Porto
826 Velho Highway (BR-319)]. *Rev Bras Meteorol* 24(2):208-233.
827 <https://doi.org/10.1590/S0102-77862009000200009> [English translation available
828 at: [http://philip.inpa.gov.br/publ_livres/mss%20and%20in%20press/RBMET-BR-](http://philip.inpa.gov.br/publ_livres/mss%20and%20in%20press/RBMET-BR-319_-engl.pdf)
829 [319_-engl.pdf](http://philip.inpa.gov.br/publ_livres/mss%20and%20in%20press/RBMET-BR-319_-engl.pdf)]

- 830 Fernandes MR (2013) Diagnóstico de dados socioeconômicos secundários dos municípios
831 de Iranduba, Manacapuru e Novo Airão – Parte I – Levantamento e sistematização
832 de dados dos Censos Agropecuários do IBGE. [Diagnosis of secondary
833 socioeconomic data on the municipalities of Iranduba, Manacapuru and Novo Airão
834 - Part I - Survey and systematization of data from the IBGE Agricultural Censuses].
835 Fundação Vitória Amazônica, Manaus, Amazonas, Brazil. 115 pp.
836 [https://www.passeidireto.com/arquivo/37999193/livro-iranduba-fva-sdt02-2014-](https://www.passeidireto.com/arquivo/37999193/livro-iranduba-fva-sdt02-2014-por-0212/16)
837 [por-0212/16](https://www.passeidireto.com/arquivo/37999193/livro-iranduba-fva-sdt02-2014-por-0212/16)
- 838 Forman RTT, Wu J (2016) Where to put the next billion people. *Nature* 537:608-611.
839 <https://doi.org/10.1038/537608a>
- 840 GEO-Cidades (2002). Relatório Ambiental Urbano Integrado de Manaus [Manaus
841 Integrated Urban Environmental Report]. Projeto GEO Cidades, Manaus,
842 Amazonas, Brazil. 187 pp. [http://www.terrabrasil.org.br/ecotecadigital/pdf/geo-](http://www.terrabrasil.org.br/ecotecadigital/pdf/geo-manau.pdf)
843 [manau.pdf](http://www.terrabrasil.org.br/ecotecadigital/pdf/geo-manau.pdf)
- 844 Hagen A (2003) Fuzzy set approach to assessing similarity of categorical maps. *Internat J*
845 *Geogr Informat Sci* 17(3):235-249. <https://doi.org/10.1080/13658810210157822>
- 846 Kirby KR, Laurance WF, Albernaz AKM, Schroth G, Fearnside PM, Bergen S,
847 Ventincinque EM, da Costa C (2005) The future of deforestation in the Brazilian
848 Amazon. *Futures* 38(4):432-453. <https://doi.org/10.1016/j.futures.2005.07.011>
- 849 Kuwahara N, Neto JCL, Abensur, TC (2012) Modelagem de previsão de navegabilidade
850 em rios da Amazônia: ferramenta web de suporte aos usuários do transporte
851 aquaviário [A forecast model for Amazon waterways: Web tool to support river
852 transportation]. *Journal of Transport Literature*, 6(3): 60-89.
853 <https://doi.org/10.1590/S2238-10312012000300005>
- 854 Laurance WF, Albernaz AKM, Schroth G, Fearnside PM, Bergen S, Ventincinque EM, da
855 Costa C (2002) Predictors of deforestation in the Brazilian Amazon. *J Biogeogr*
856 29:737-748. <https://doi.org/10.1046/j.1365-2699.2002.00721.x>
- 857 Laurance WF, Camargo JLC, Fearnside PM, Lovejoy TE, Williamson GB, Mesquita RCG,
858 Meyer CFJ, Bobrowiec PED, Laurance SGW (2018) An Amazonian rainforest and
859 its fragments as a laboratory of global change. *Biological Reviews*, 93(1):223–247.
860 <https://doi.org/10.1111/brv.12343>
- 861 Liu Z, Robinson GM (2016) Residential development in the peri-urban fringe: The example
862 of Adelaide, South Australia. *Land Use Policy* 57:179-192.
863 <https://doi.org/10.1016/j.landusepol.2016.05.026>
- 864 Maciel JB, Lima MC (2013) A metropolização do espaço em Iranduba: Uma nova
865 configuração com expansão imobiliária [The metropolitization of space in Iranduba:
866 A new configuration with real-estate expansion]. In: II Simpósio de Estudos
867 Urbanos – A Dinâmica das Cidades e Produção do Espaço. Universidade Estadual
868 do Paraná, Campo Mourão, Paraná, Brazil. 24 pp
869 http://www.fecilcam.br/anais/ii_seurb/documentos/maciel-jesse-burlamaque.pdf
- 870 Moreira F, Fontes I, Dias S, Batista e Silva J, Loupa-Ramos I (2016) Contrasting static
871 versus dynamics-based typologies of land cover patterns in the Lisbon metropolitan
872 area: Towards a better understanding of peri-urban areas. *Applied Geogr* 75:49-59.
873 <https://doi.org/10.1016/j.apgeog.2016.08.004>
- 874 Moreira MP, Santos CJ, Ferreira OJMR (2009) Desflorestamento ao longo das estradas
875 AM-070 (Manaus/Iranduba/Manacapuru) e AM-352 (Manacapuru/Novo Airão) na
876 Amazônia Central: Subsídios para o planejamento [Deforestation along the AM-070

- 877 (Manaus-Iranduba-Manacapuru) and AM-352 (Manacapuru-Novo Airão) roads in
 878 central Amazonia: Contributions to planning]. In: Anais XIV Simpósio Brasileiro de
 879 Sensoriamento Remoto, Natal, RN. Instituto Nacional de Pesquisas Espaciais
 880 (INPE), São José dos Campos, São Paulo, Brazil. pp 747-754.
 881 <http://marte.sid.inpe.br/col/dpi.inpe.br/sbsr@80/2008/11.11.15.11/doc/747-754.pdf>
- 882 Nepstad DC, McGrath DG, Soares-Filho B (2011) Systemic conservation, REDD, and the
 883 future of the Amazon basin. *Conserv Biol* 25:1113-1116.
 884 <https://doi.org/10.1111/j.1523-1739.2011.01784.x>
- 885 Nogueira EM, Yanai AM, Vasconcelos SS, Graça PMLA, Fearnside PM (2018) Carbon
 886 stocks and losses to deforestation in protected areas in Brazilian Amazonia. *Reg*
 887 *Environ Change* 18(1):261-270. <https://doi.org/10.1007/s10113-017-1198-1>
- 888 Rodrigues HO, Soares-Filho BS, Costa WLS (2007) Dinamica EGO, uma plataforma para
 889 modelagem de sistemas ambientais [Dinamica EGO, a platform for modeling of
 890 environmental systems]. In: XIII Simpósio Brasileiro de Sensoriamento Remoto,
 891 Florianópolis, Santa Catarina. Instituto Nacional de Pesquisas Espaciais (INPE),
 892 São José dos Campos, SP, Brazil. pp 3089-3096.
 893 <http://marte.sid.inpe.br/col/dpi.inpe.br/sbsr@80/2006/11.06.17.59/doc/3089-3096.pdf>
- 894
 895 Rodrigues MS, Pedrollo CT, Borges SH, Camargo YR, Moreira MP, Amaral GS, Brandão
 896 DO, Iwanaga S (2014) Iranduba: Características Socioambientais de um Município
 897 em Transformação [Iranduba: Social and Environmental Characteristics of a
 898 Municipality in Transformation]. Documentos Técnicos, Fundação Vitória
 899 Amazônica, Manaus, Amazonas, Brazil. 24 pp
 900 <https://pt.scribd.com/document/367109685/Livro-Iranduba-FVA-SDT02-2014-POR-02-12>
- 901
 902 Sá MTV, da Silva CEM, Sá LYBAV (2010) A ponte sobre o Rio Negro e seus impactos
 903 [The bridge over the Rio Negro and its impacts]. *T&C Amazônia* 18:11-17.
 904 http://tecamazonia.com.br/wp-content/uploads/2017/03/revista_tec_ed18.pdf
- 905 Sant'Anna JA (1998) Rede básica de transporte na Amazônia [Basic transportation network
 906 in Amazonia]. Brasília, DF, Brazil: Instituto de Pesquisa Econômica Aplicada
 907 (IPEA). http://www.ipea.gov.br/agencia/images/stories/PDFs/TDs/td_0562.pdf
- 908 Santé I, García AM, Miranda D, Crecente R (2010) Cellular automata models for the
 909 simulation of real-world processes: A review and analysis. *Landscape Urban Plan*
 910 96(2):108-122. <https://doi.org/10.1016/j.landurbplan.2010.03.001>
- 911 Shi Y, Sun X, Zhu X, Li Y, Mei L (2012) Characterizing growth types and analyzing
 912 growth density distribution in response to urban growth patterns in peri-urban areas
 913 of Lianyungang City. *Landscape Urban Plan* 105(4):425-433.
 914 <https://doi.org/10.1016/j.landurbplan.2012.01.017>
- 915 Soares-Filho BS, Cerqueira G, Araújo W, Voll E (2007) Modelagem de dinâmica de
 916 paisagem: Concepção e potencial de aplicação de modelos de simulação baseados
 917 em autômato celular [Modeling landscape dynamics: Design and potential
 918 application of simulation models based on cellular automata]. *Megadiversidade*
 919 3:74-86.
 920 http://www.conservation.org/global/brasil/publicacoes/Documents/megadiversidade_v3_n1_2_dez_2007.pdf
- 921

- 922 Soares-Filho BS, Nepstad DC, Curran LM, Cerqueira GC, Garcia RA, Ramos CA, Voll E,
923 McDonald A, Lefebvre P, Schlesinger P (2006) Modelling conservation in the
924 Amazon basin. *Nature* 440:520-523. <https://doi.org/doi:10.1038/nature04389>
- 925 Soares-Filho BS, Pennachin CL, Cerqueira G (2002) DINAMICA – a stochastic cellular
926 automata model designed to simulate the landscape dynamics in an Amazonian
927 colonization frontier. *Ecol Modelling* 154(3):217-235.
928 [https://doi.org/10.1016/S0304-3800\(02\)00059-5](https://doi.org/10.1016/S0304-3800(02)00059-5)
- 929 Soares-Filho BS, Rodrigues HO, Costa WL (2009) Modeling Environmental Dynamics
930 with Dinamica EGO. Centro de Sensoriamento Remoto, Universidade Federal de
931 Minas Gerais, Belo Horizonte, MG, Brazil. 115 pp.
932 http://www.csr.ufmg.br/dinamica/tutorial/Dinamica_EGO_guidebook.pdf
- 933 Sousa IS (2011) Grandes projetos na Amazônia: mudanças e perspectivas na produção do
934 espaço urbano em Iranduba – AM.[Great projects in the Amazon: changes and
935 prospects in the production of urban space in Iranduba – AM]. *Acta Geográfica* 5
936 (11):71-80. <https://doi.org/10.5654/actageo2011.0001.0005>
- 937 Sousa IS (2015) A ponte Rio Negro e a reestruturação do espaço na Região Metropolitana
938 de Manaus: Um olhar a partir de Iranduba e Manacapuru [The Rio Negro Bridge
939 and the restructuring of space in the Manaus Metropolitan Region: A view from
940 Iranduba and Manacapuru], Editora Reggo and UEA Edições, Manaus, AM, Brazil.
941 176 pp
- 942 Souza Jr C, Brandão Jr A, Anderson A, Veríssimo A (2005) The expansion of unofficial
943 roads in the Brazilian Amazon. Instituto do Homem e Meio Ambiente na Amazônia
944 (IMAZON), Belém, Pará, Brazil. O Estado da Amazônia 1:1-2.
945 <http://g7negocios.com.br/imazon/publicacoes/the-expansion-of-unofficial-roads-in-the-brazilian-amazon/?lang=en>
- 947 Sparovek G, Bernds G, Barreto AG, Klug ILF (2012) The revision of the Brazilian Forest
948 Act: Increased deforestation or a historic step towards balancing agricultural
949 development and nature conservation? *Environ Sci Pol* 16:65-72.
950 <https://doi.org/10.1016/j.envsci.2011.10.008>
- 951 Su S, Wang Y, Luo F, Mai G, Pu J (2014) Peri-urban vegetated landscape pattern changes
952 in relation socioeconomic development. *Ecolog Indicators* 46:477-486.
953 <https://doi.org/10.1016/j.ecolind.2014.06.044>
- 954 Swetnam RD, Fisher B, Mbilinyi, BP, Munishi PKT, Willcock S, Ricketts T, Mwakalila S,
955 Balmford A, Burgess ND, Marshall AR, Lewis SL (2011) Mapping socio-economic
956 scenarios of land cover change: A GIS method to enable ecosystem service
957 modeling. *J Environ Manage* 92:563-574.
958 <https://doi.org/10.1016/j.jenvman.2010.09.007>
- 959 Tacoli C (2003) The links between urban and rural development. *Environ and Urbanisation*
960 15(3):3-12. <https://doi.org/10.1177/095624780301500111>
- 961 Wang H, Qiu F (2017) Investigating the impact of agricultural land losses on deforestation:
962 Evidence from a peri-urban area in Canada. *Ecol Econ* 139:9-18.
963 <https://doi.org/10.1016/j.ecolecon.2017.04.002>
- 964 Yanai AM, Fearnside PM, Graça PMLA, Nogueira EM (2012) Avoided deforestation in
965 Brazilian Amazonia: Simulating the effect of the Juma Sustainable Development
966 Reserve. *Forest Ecol Manage* 282:78-91.
967 <https://doi.org/10.1016/j.foreco.2012.06.029>

- 968 Yanai AM, Nogueira EM, Graça PMLA, Fearnside PM (2017) Deforestation and carbon-
 969 stock loss in Brazil's Amazonian settlements. *Environmental Management* 59(3)
 970 393-409. <https://doi.org/10.1007/s00267-016-0783-2>
 971 Yeh AG-O, Li X (2006) Errors and uncertainties in urban cellular automata. *Computers,*
 972 *Environ and Urban Systems* 30:10-28.
 973 <https://doi.org/10.1016/j.compenurbsys.2004.05.007>
 974 Yu XJ, Ng CN (2007) Spatial and temporal dynamics of urban sprawl along two urban-
 975 rural transects: A case study of Guangzhou, China. *Landscape Urban Plan* 79(1):96-
 976 109. <https://doi.org/10.1016/j.landurbplan.2006.03.008>

977 **Figure legends**

- 978
 979
 980 Figure 1. Map of the Manaus Metropolitan Region (MMR), which was created in 2007
 981 encompassing the city of Manaus and several municipalities in Brazil's state of
 982 Amazonas.
 983
 984 Figure 2. Map of deforestation by 2010 based on PRODES data from Brazil, INPE (2018)
 985 (A). And regionalization of the study area based on road density: A- High density;
 986 B- Average density; C- Low density, D-Very low density and E- River access (B).
 987
 988 Figure 3. Cumulative area (ha) of deforestation from 2011 to 2030 simulated for each
 989 scenario for the study area as a whole and for each road-density region on the right
 990 bank of the Rio Negro under direct influence of the bridge.
 991
 992 Figure 4. Simulated map of land-cover dynamics by 2030 for the No-bridge scenario (A)
 993 and for the area nearest to Manaus (B). Simulated map of land-cover dynamics by
 994 2030 for the Bridge scenario (C) and for the area along Highway AM-352 (D).
 995

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
Dynamic variables	Road network	Updated from data provided by Remote Sensing Center of the Federal University of Minas Gerais
	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)

997

998 **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.

999

1000 **Table 3. Deforestation and forest area (ha) inside and outside of the “agrarian forest**
 1001 **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

1002

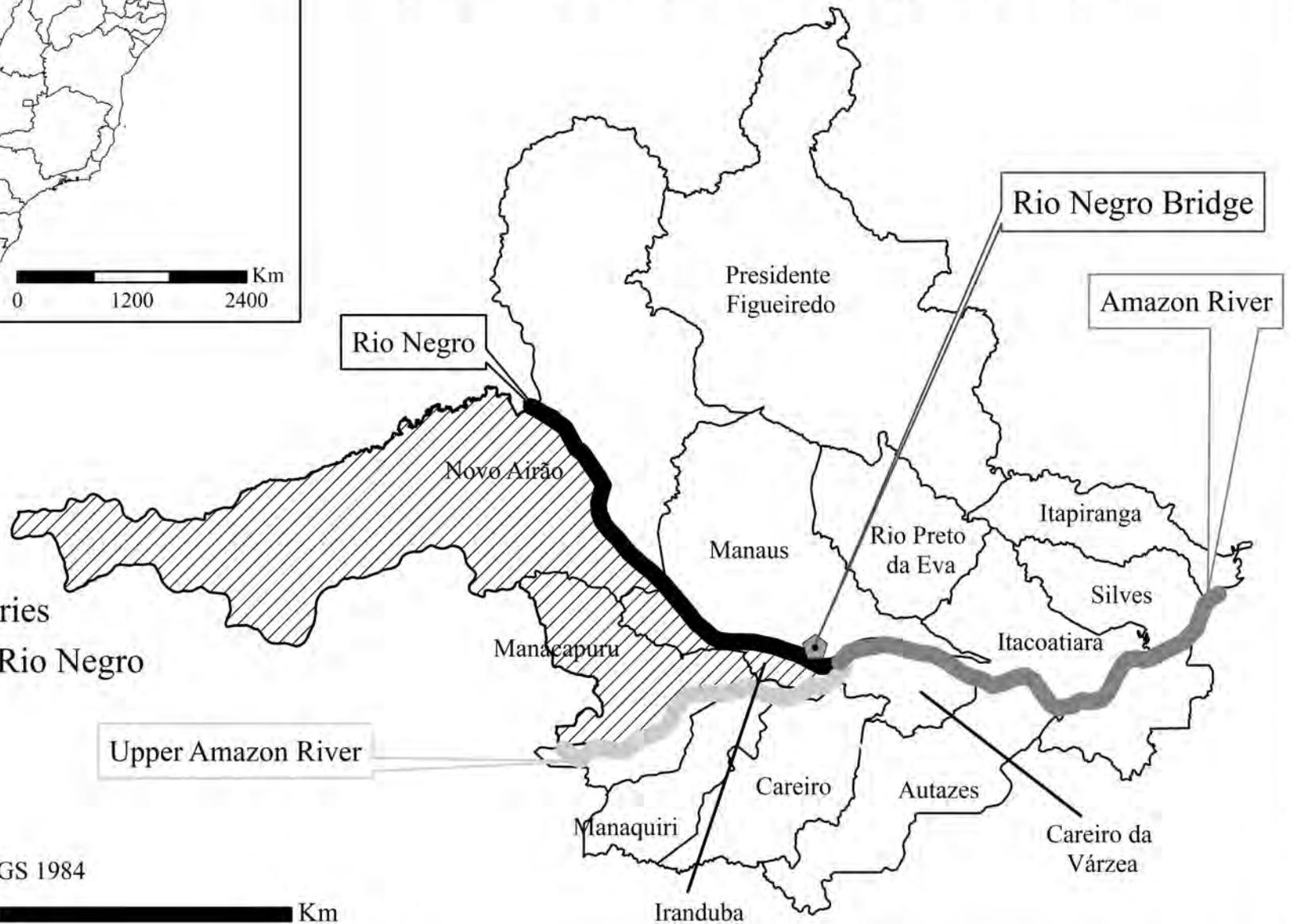
64°0'0"W

62°0'0"W

60°0'0"W

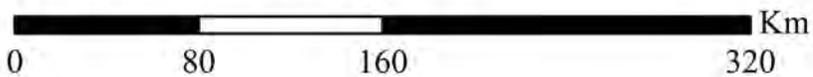
58°0'0"W

Manaus Metropolitan Region (MMR)



-  Municipal boundaries
-  Right bank of the Rio Negro

Map projection
 UTM Zone 20 S - Datum WGS 1984



0°0'0"

2°0'0"S

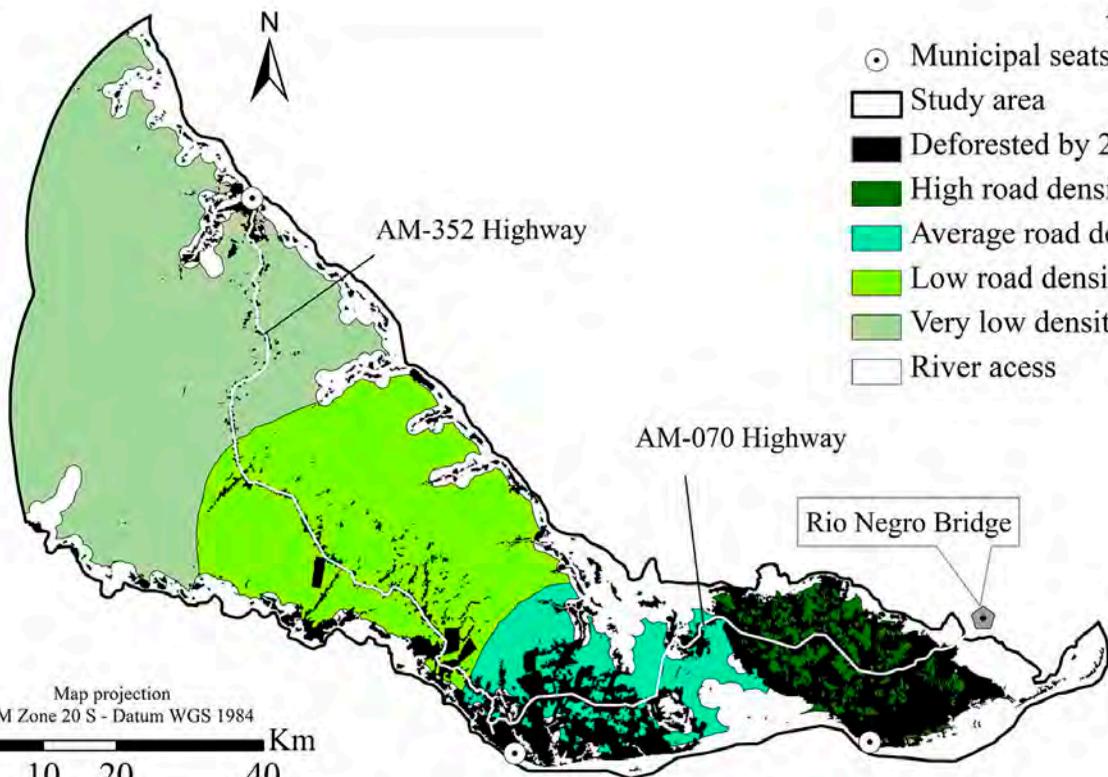
4°0'0"S

61°00'W

60°00'W

A

- Municipal seats
- Study area
- Deforested by 2010
- High road density
- Average road density
- Low road density
- Very low density
- River access



2°30'0"S

3°0'0"S

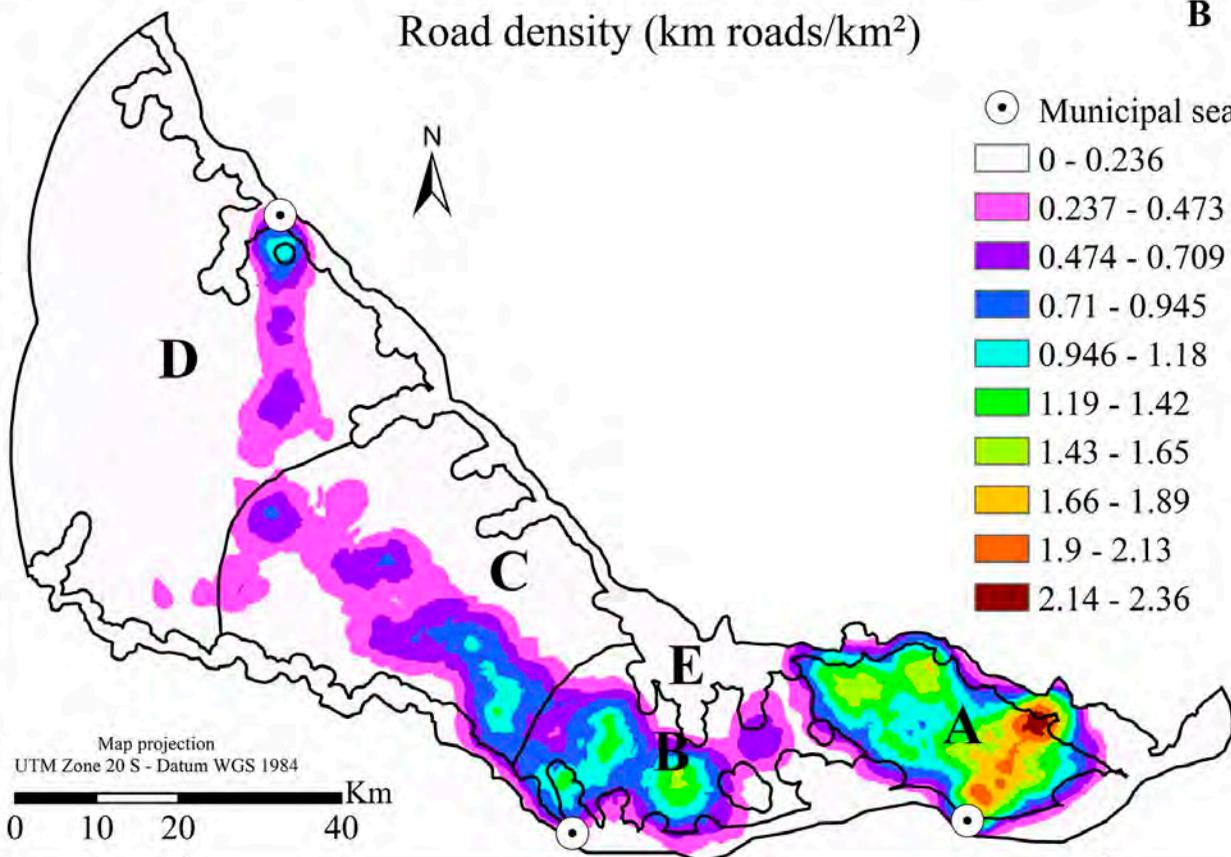
61°30'W

60°20'W

B

Road density (km roads/km²)

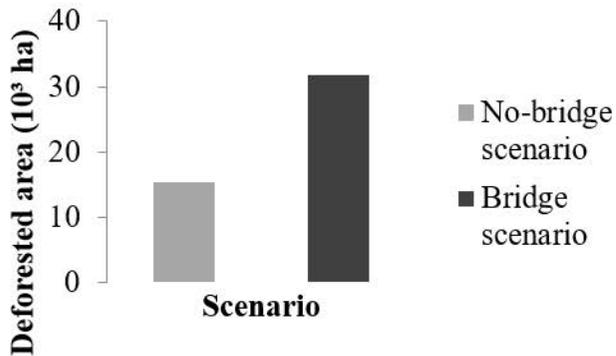
- Municipal seats
- 0 - 0.236
- 0.237 - 0.473
- 0.474 - 0.709
- 0.71 - 0.945
- 0.946 - 1.18
- 1.19 - 1.42
- 1.43 - 1.65
- 1.66 - 1.89
- 1.9 - 2.13
- 2.14 - 2.36



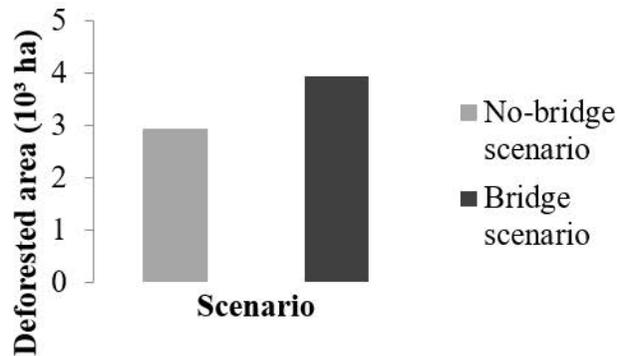
2°41'0"S

3°12'0"S

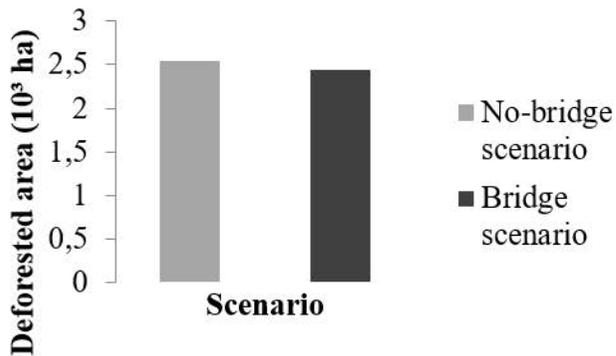
Study area



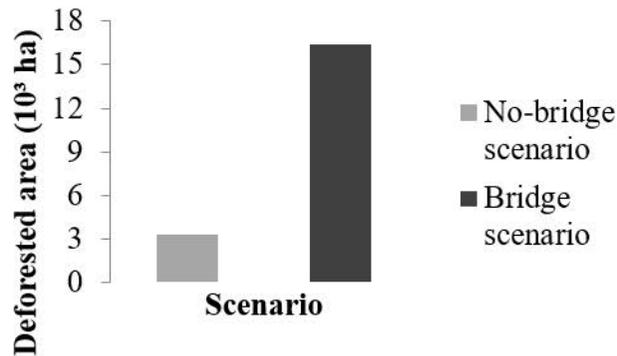
"High road density"



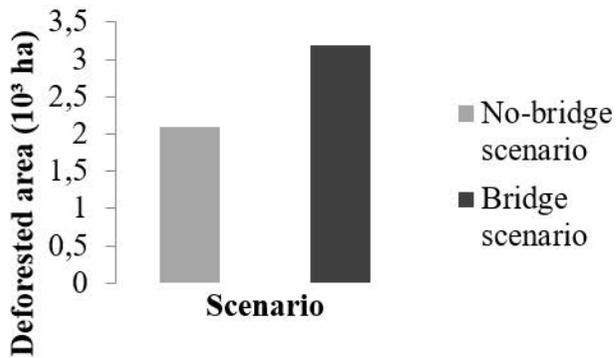
"Average road density"



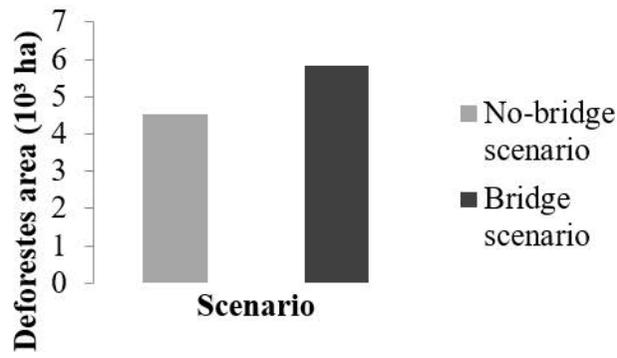
"Low road density"



"Very low road density"

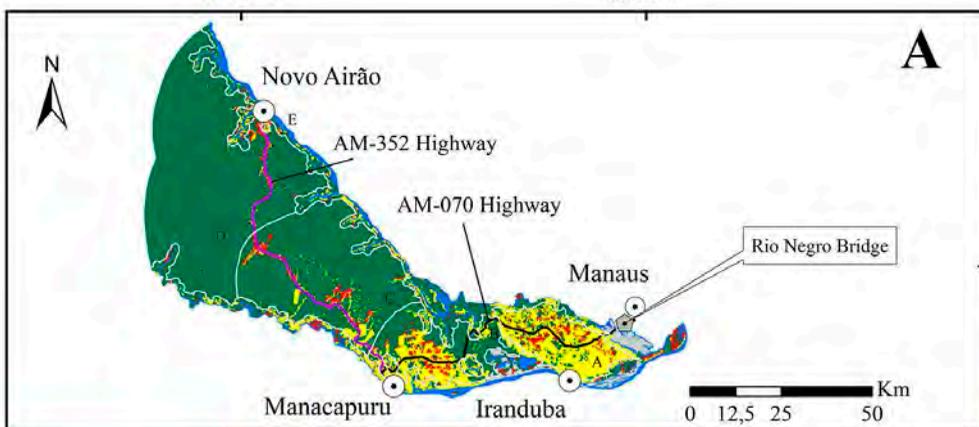


"River access"



61°0'0"W

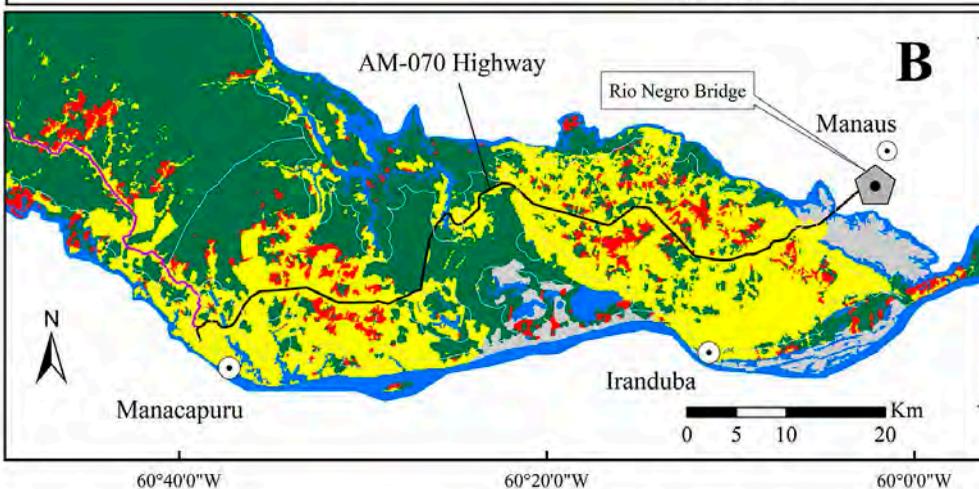
60°0'0"W



No-bridge Scenario

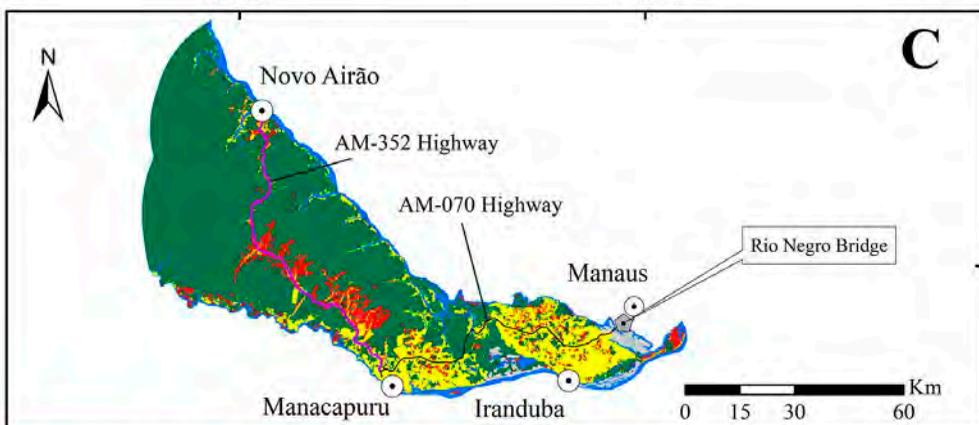
- Municipal seats
- Deforestation by 2011
- Forest
- Deforested by 2030
- Watercourses
- Non-forest

Map projection
UTM Zone 20 S
Datum WGS 1984

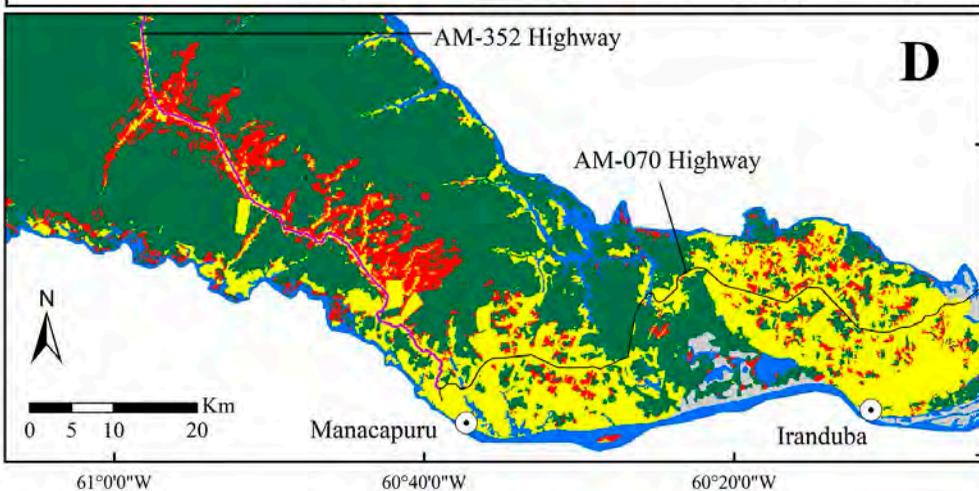


61°0'0"W

60°0'0"W



Bridge Scenario





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 Ramos¹ (camilajramos@gmail.com)

Paulo Maurício Lima de Alencastro Graça^{2,3} (pmlag@inpa.gov.br)

Philip Martin Fearnside^{2,3, *} (pmfearn@inpa.gov.br)

¹Programa de Pós Graduação em Ecologia, Instituto Nacional de Pesquisas da Amazônia (INPA), Av. André Araújo, 2936, Manaus, Amazonas, 69067-375, Brazil

²Coordenação de Dinâmica Ambiental, Instituto Nacional de Pesquisas da Amazônia (INPA), Av. André Araújo, 2936, Manaus, Amazonas, 69067-375, Brazil

³Brazilian 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.....	3
Appendix 2. Maps of attractiveness and friction for road construction.....	3
Appendix 3. Periods used to calibrate the scenarios	3
Appendix 4. Map Correlation Analysis.....	3
Appendix 5. Updating the rates of transition.....	3
Appendix 6. History of deforestation for each road-density region.	4
Appendix 7. Uncertainties and improvements in modeling.....	4
Tables	5
Table S-1. Values adopted for building the maps of attractiveness and friction for road construction.	
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)	
Table S-3. Validation of the amount of land-cover change by region in the simulated maps as compared to the observed maps.	
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).	
Table S-5. History of deforestation rate by road-density region for each calibration period according to data from Brazil, INPE (2017).	
Figures	11
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 developed in the present study.	
Figure S-4. Flow diagram of the conceptual model of land-use and cover change using Dinamica-EGO.	
Figure S-5. History of deforestation rate to study area according to data from Brazil, INPE (2017).	
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. 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).	
Figure S-11. Protected areas in the study area; data obtained from Brazil, MMA (2015).	
References	32

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).

Scenario/ Years	Region									
	High road density		Average road density		Low road density		Very low road density		River access	
	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										
Scenario/ Years	High road density		Average road density		Low road density		Very low road density		River access	
	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

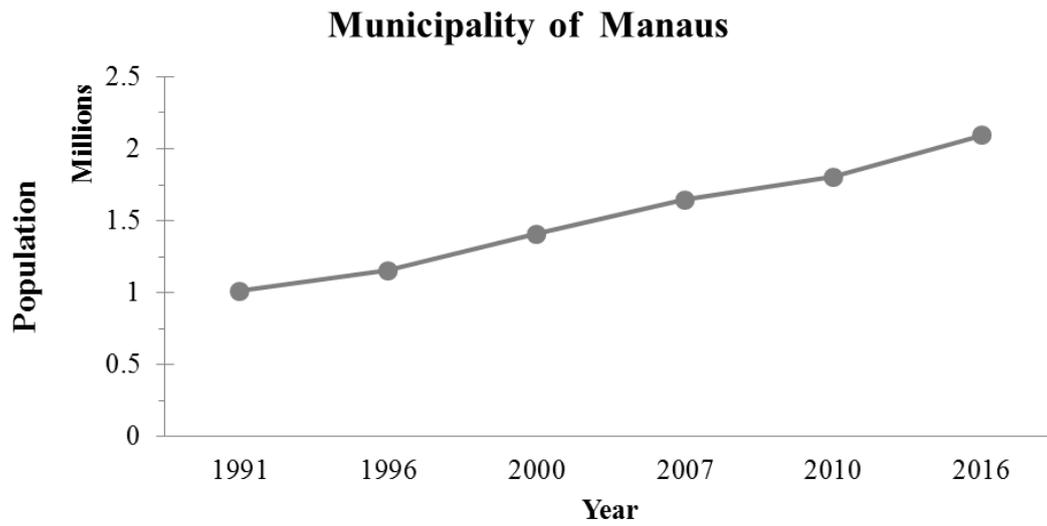


Figure S-1. Population growth data for the municipality of Manaus. Data source: Brazil, IBGE (2017): Demographic Census 1991, Population count 1996, Demographic Census 2000, Population count 2007, Demographic Census 2010 and Estimated Population 2016.

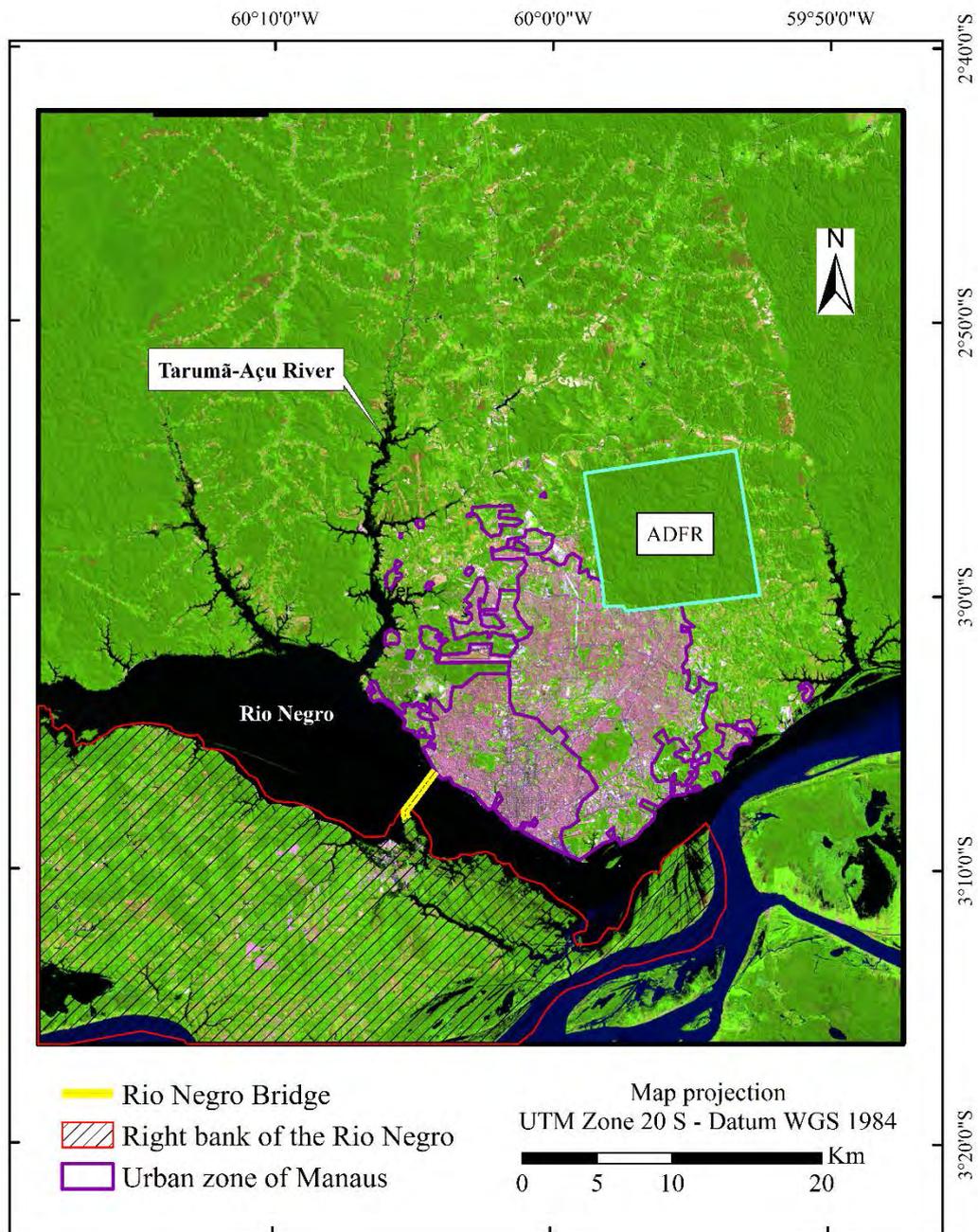


Figure S-2. Map of the connection created between the city of Manaus and the study area. ADFR = Adolpho Ducke Forest Reserve.

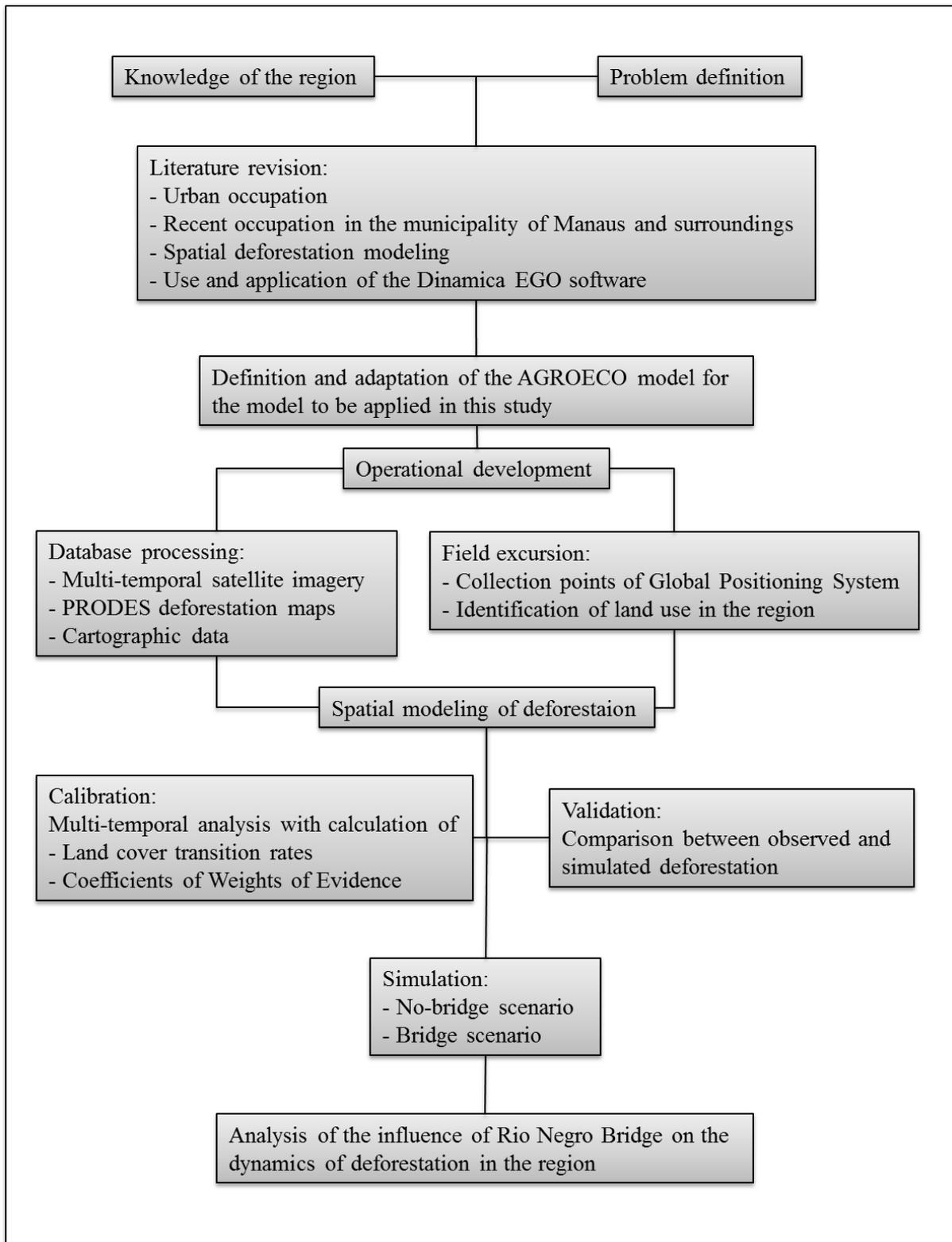


Figure S-3. Flowchart of the conceptual steps in the present study.

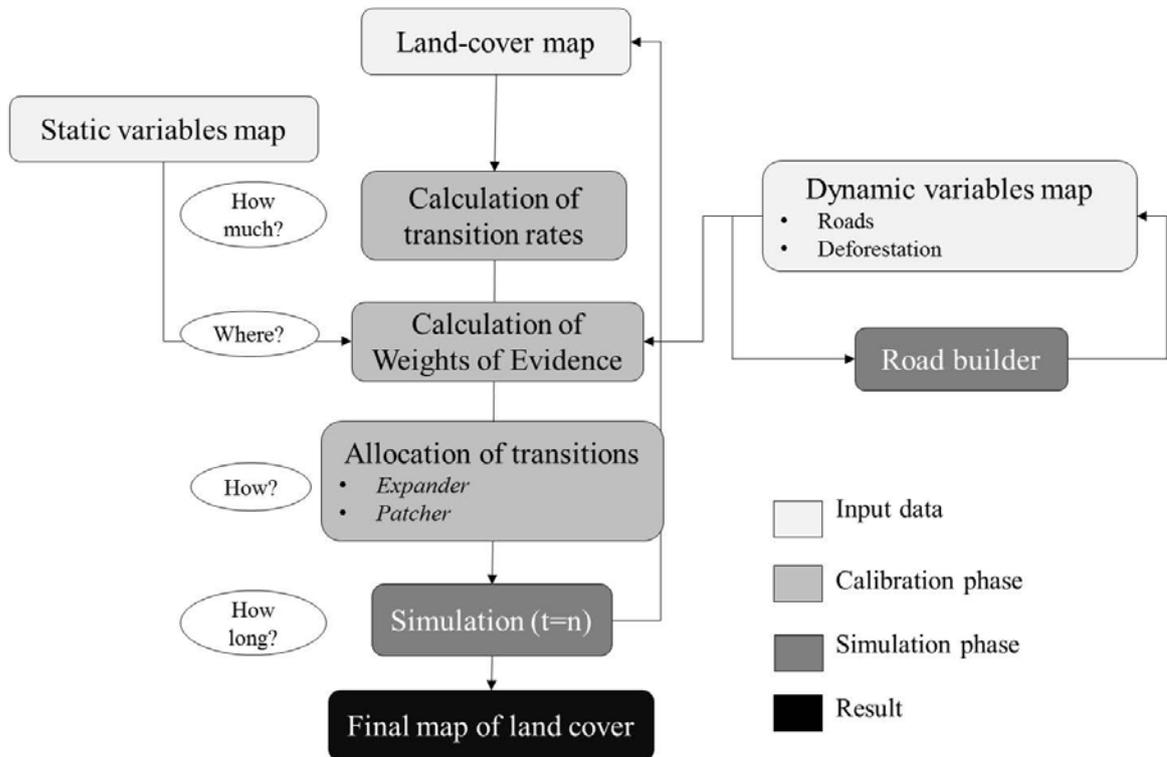


Figure S-4. Flowchart of the conceptual model of land-use and cover change using Dinamica-EGO (Adapted from Vitel 2009).

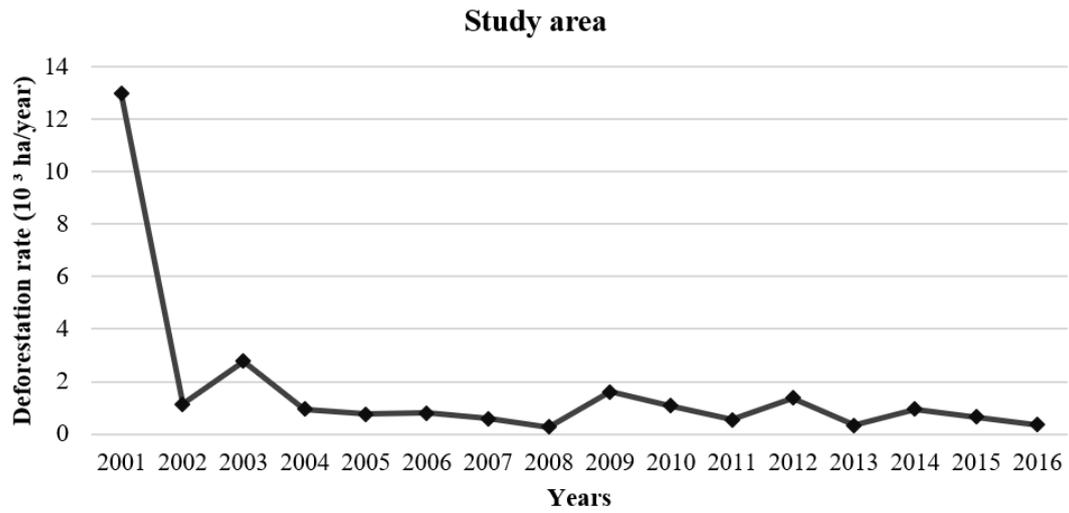
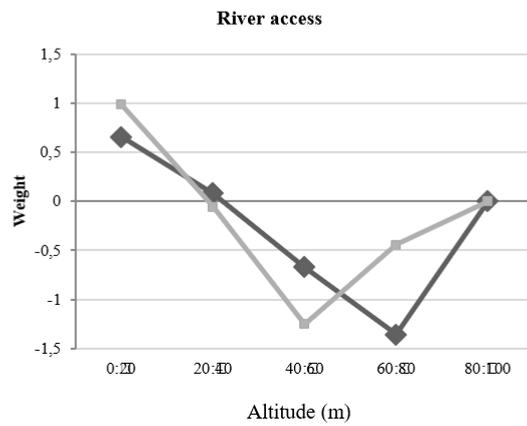
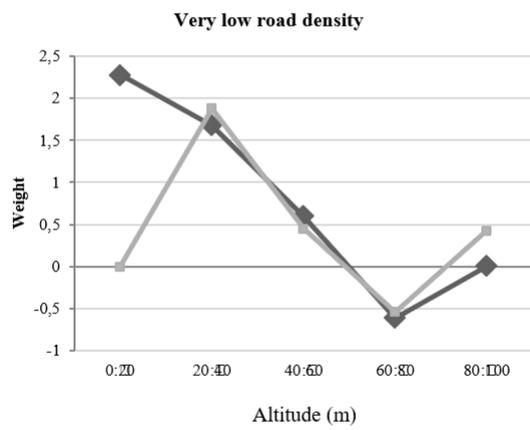
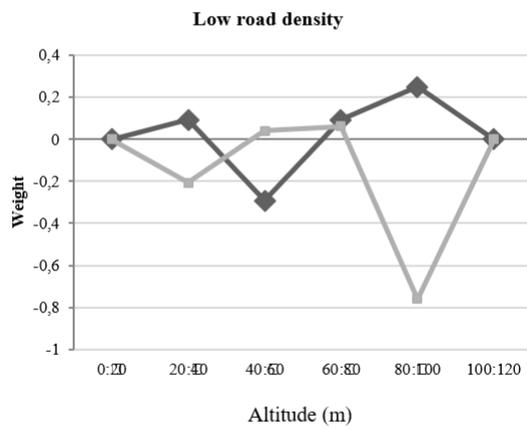
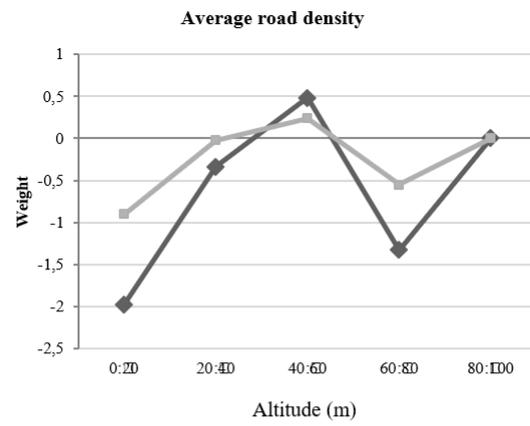
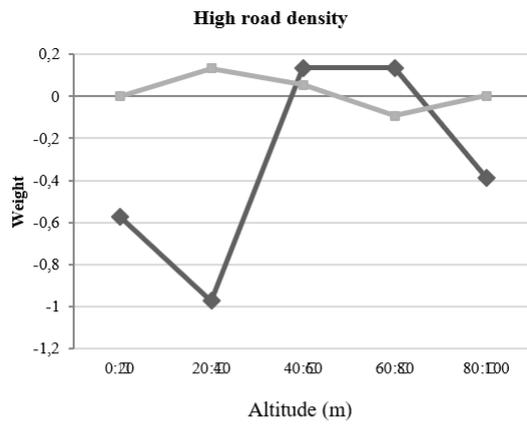


Figure S-5. History of deforestation rate to study area according to data from Brazil, INPE (2017).

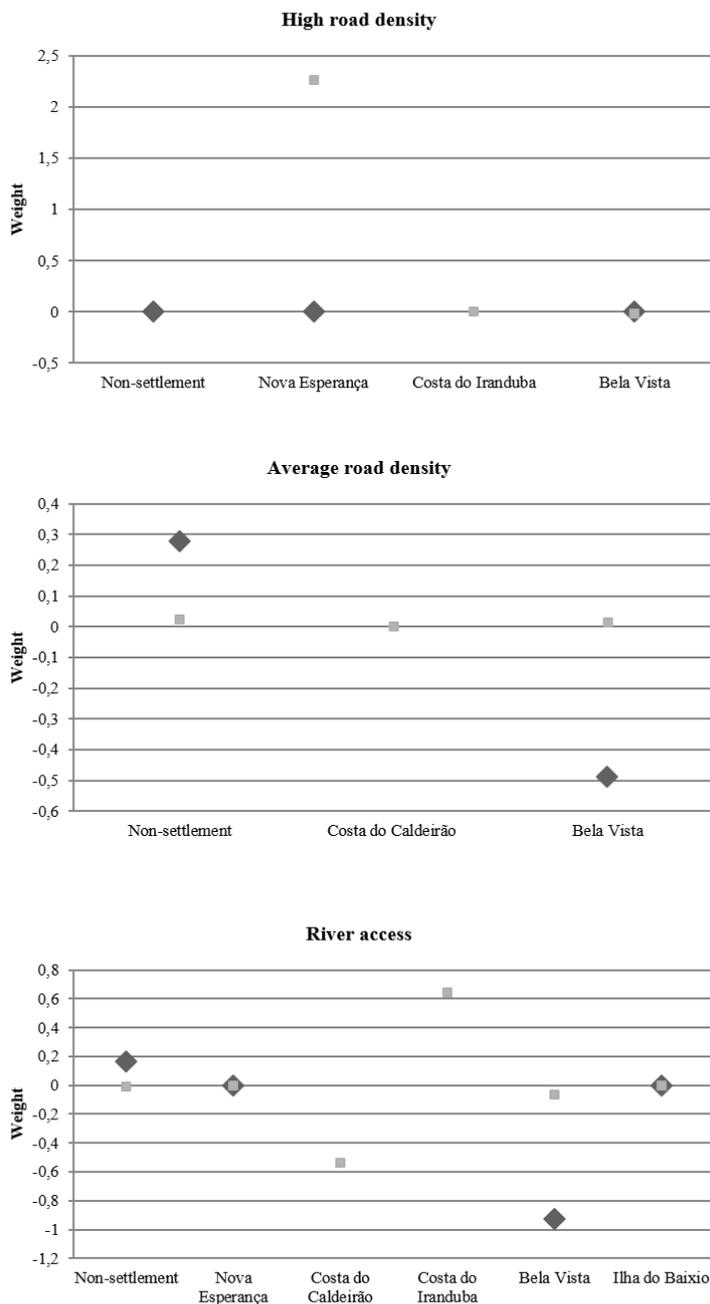
Altitude

A



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

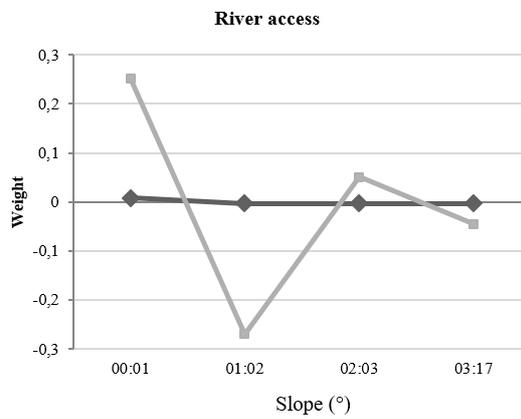
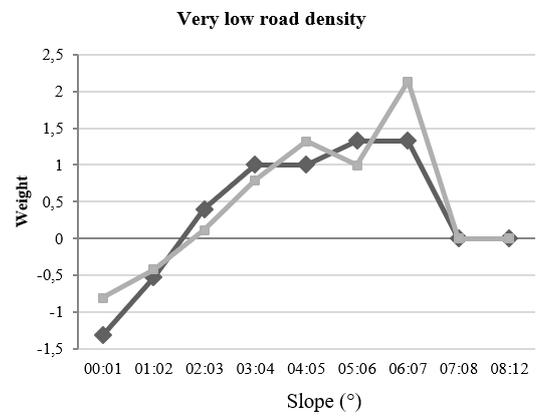
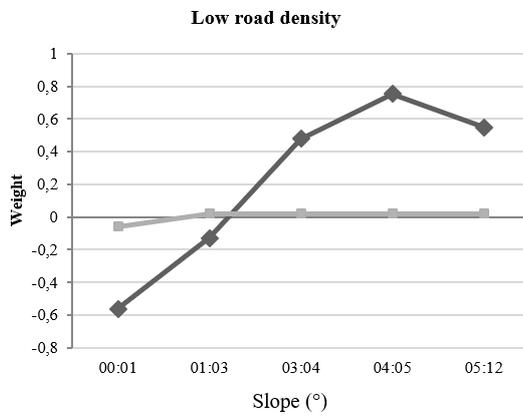
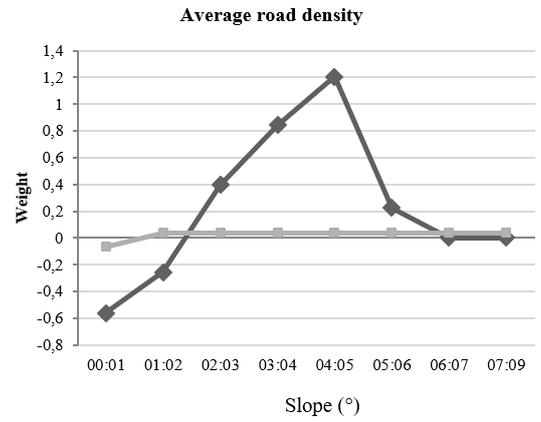
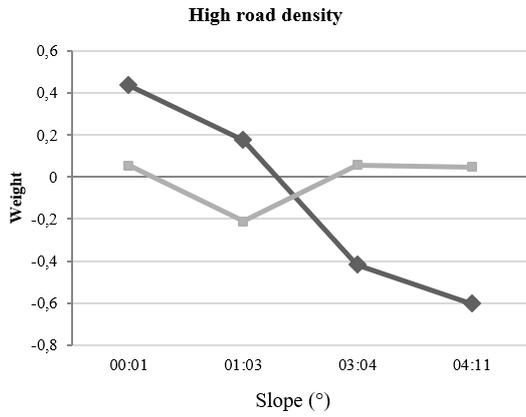
Settlements



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

Slope

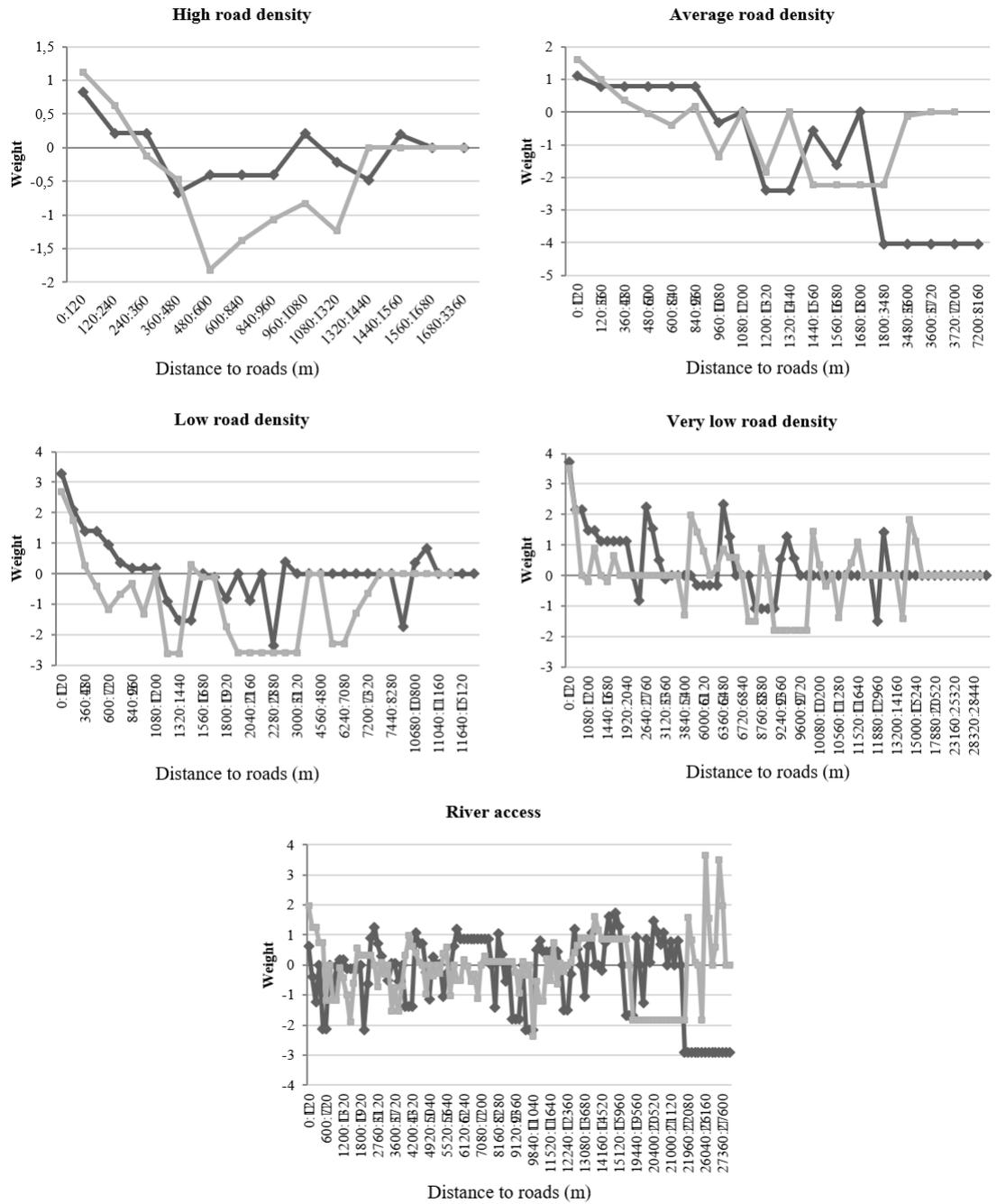
C



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

Distance to roads

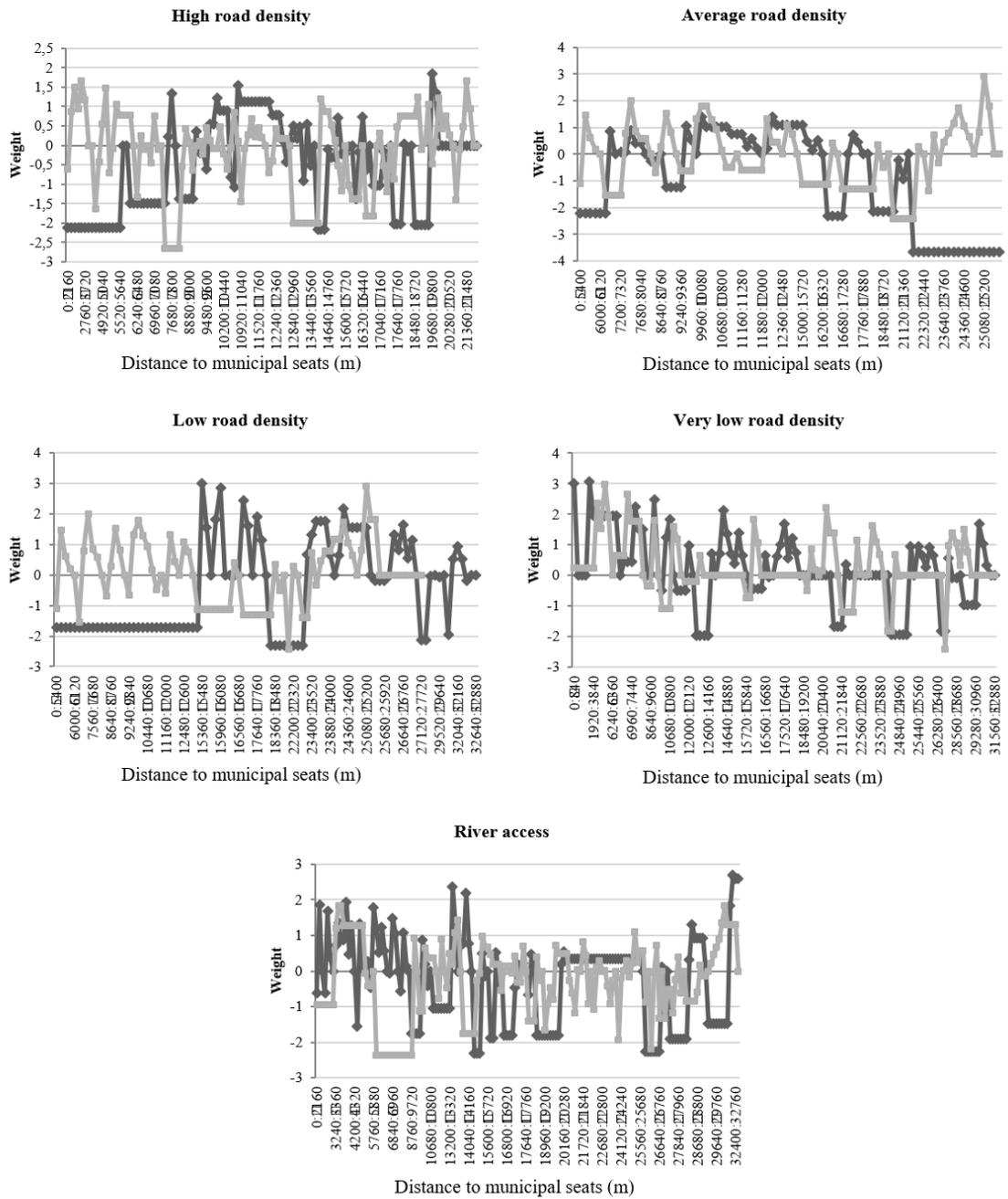
D



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

Distance to municipal seats

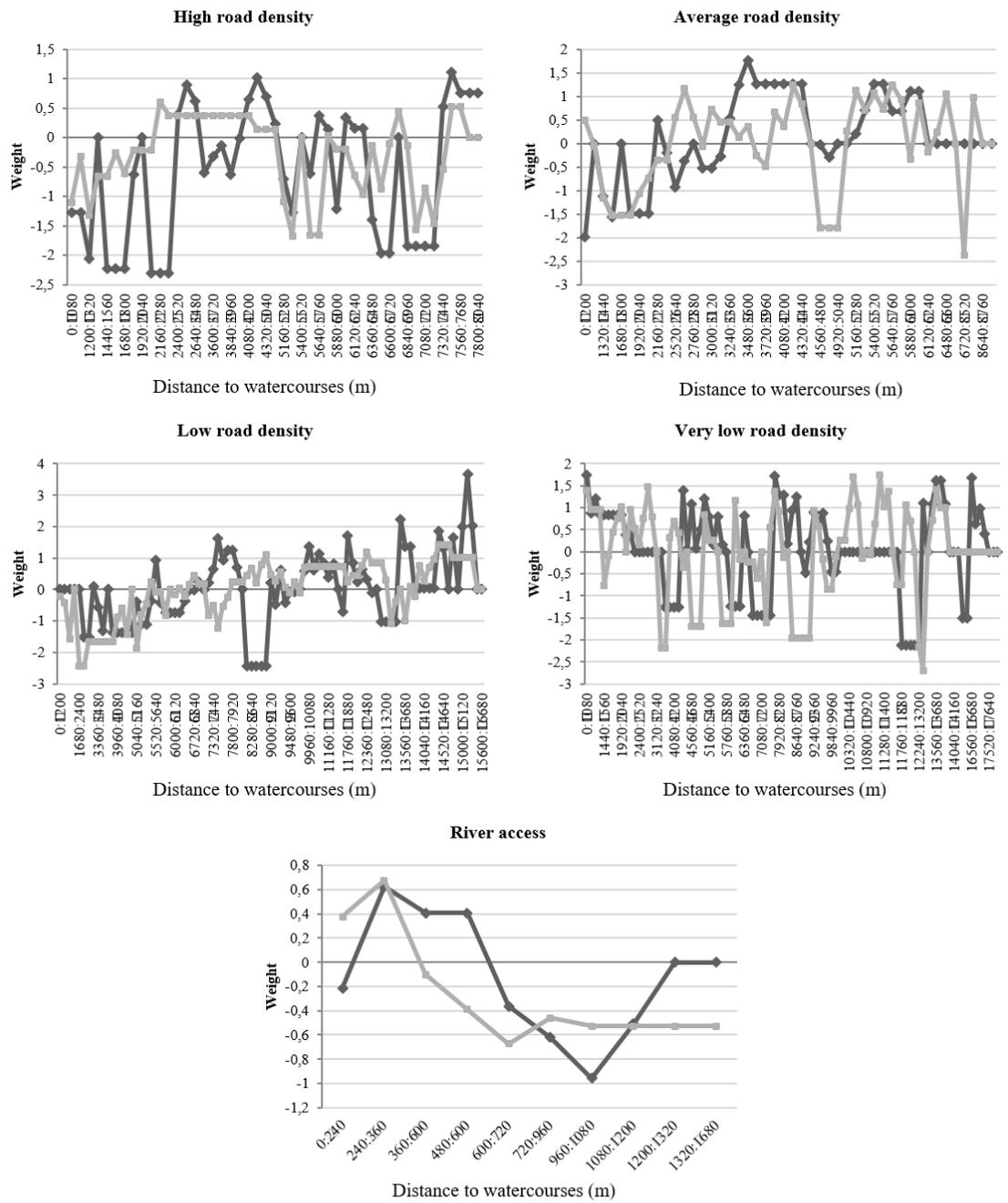
E



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

Distance to watercourses

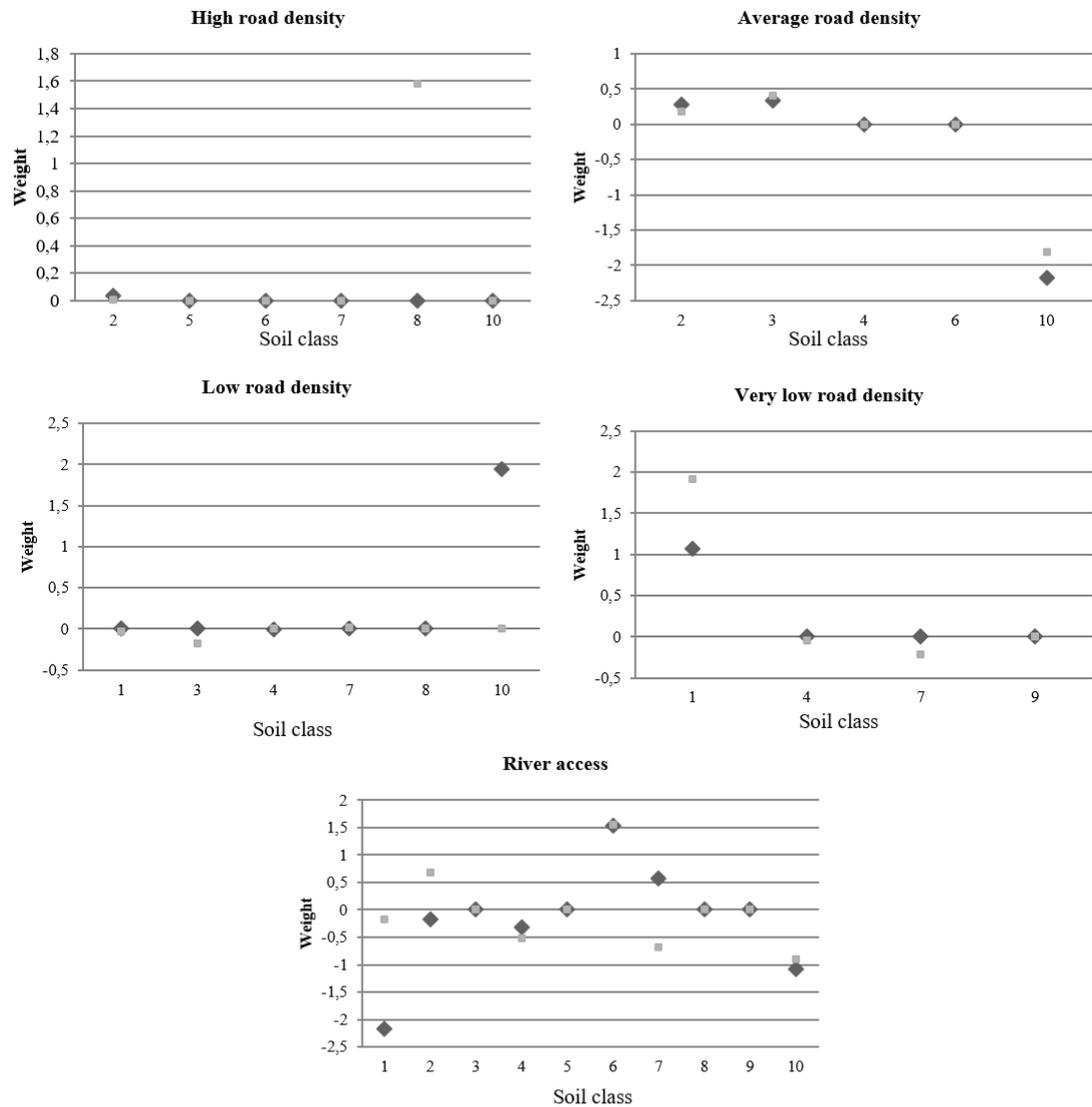
F



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

Soil

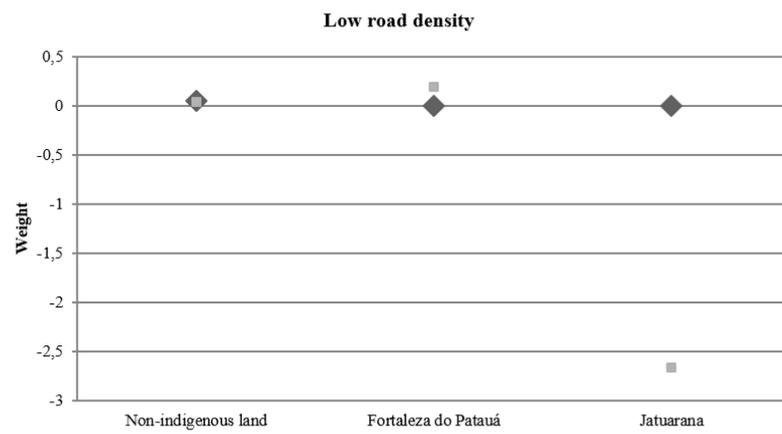
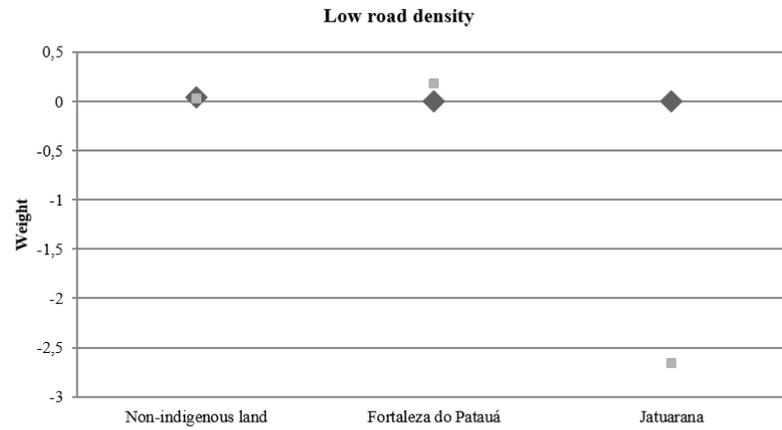
G



Legend: 1 = *Podzólico vermelho amarelo (Argissolo)* [Ultisol; Acrisol], 2 = *Latossolo amarelo (Latossolo)* [Oxisol; Ferralsol], 3 = *Petroplintico (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

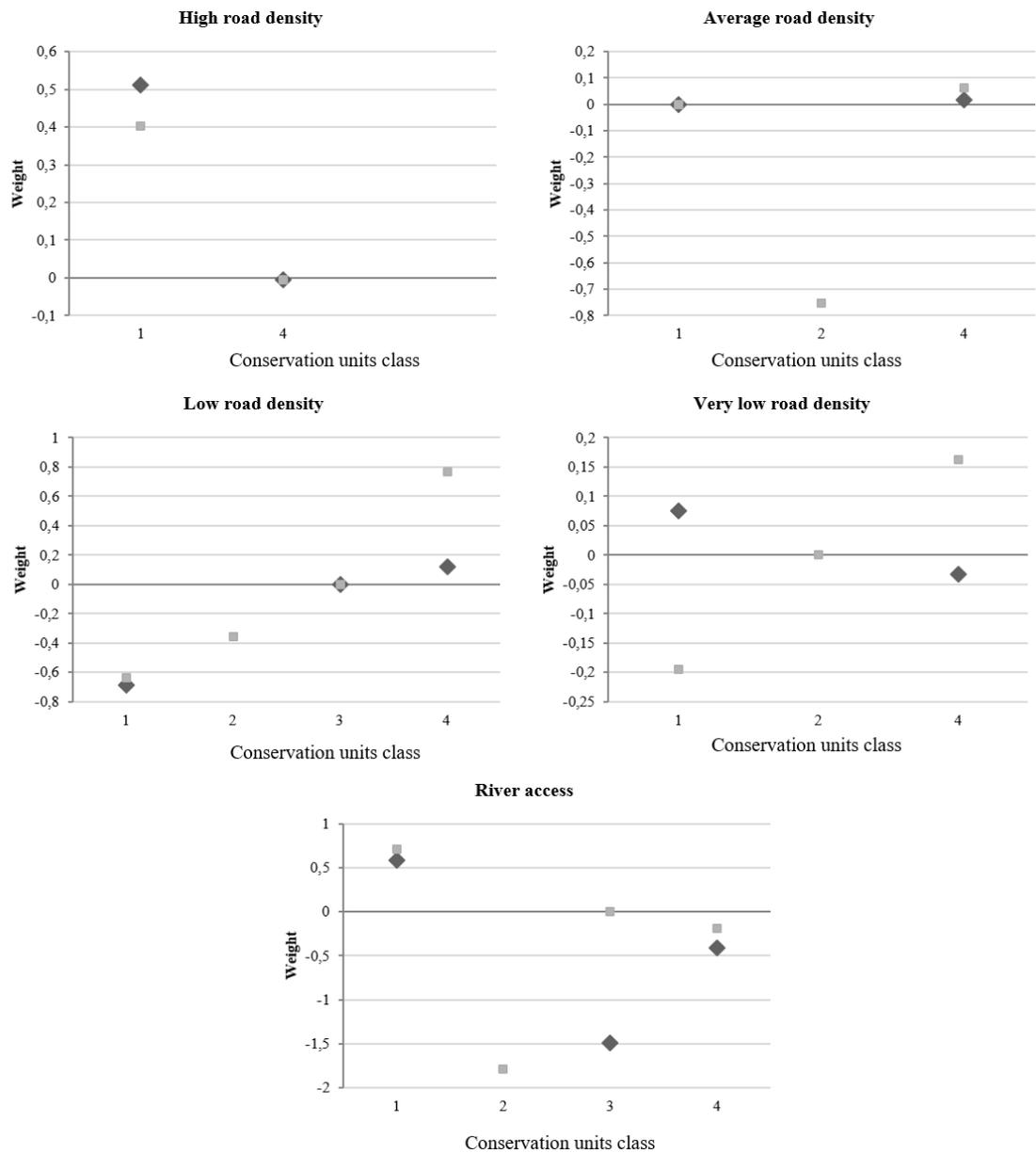
H



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

Conservation units

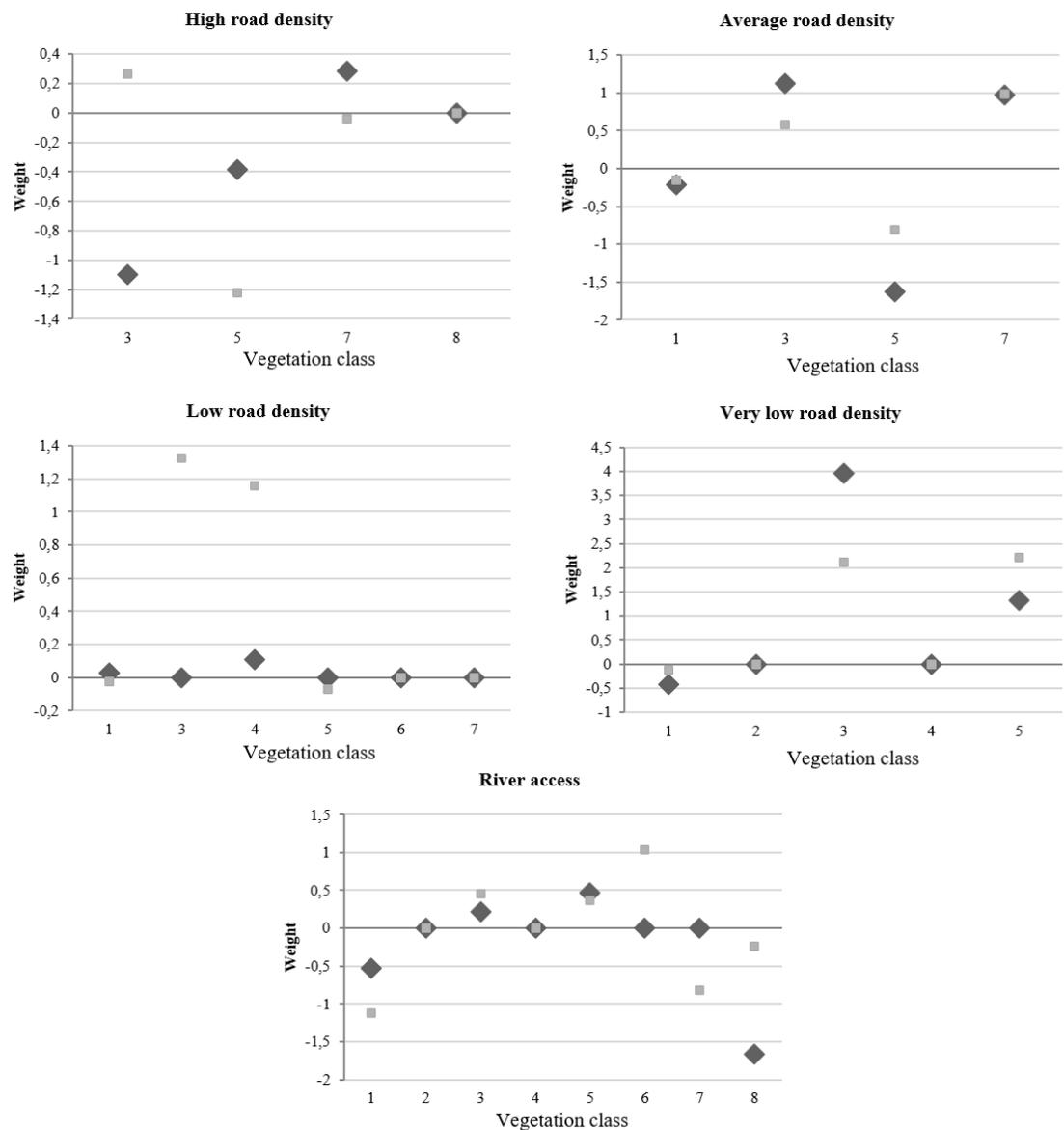
I



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.

Vegetation

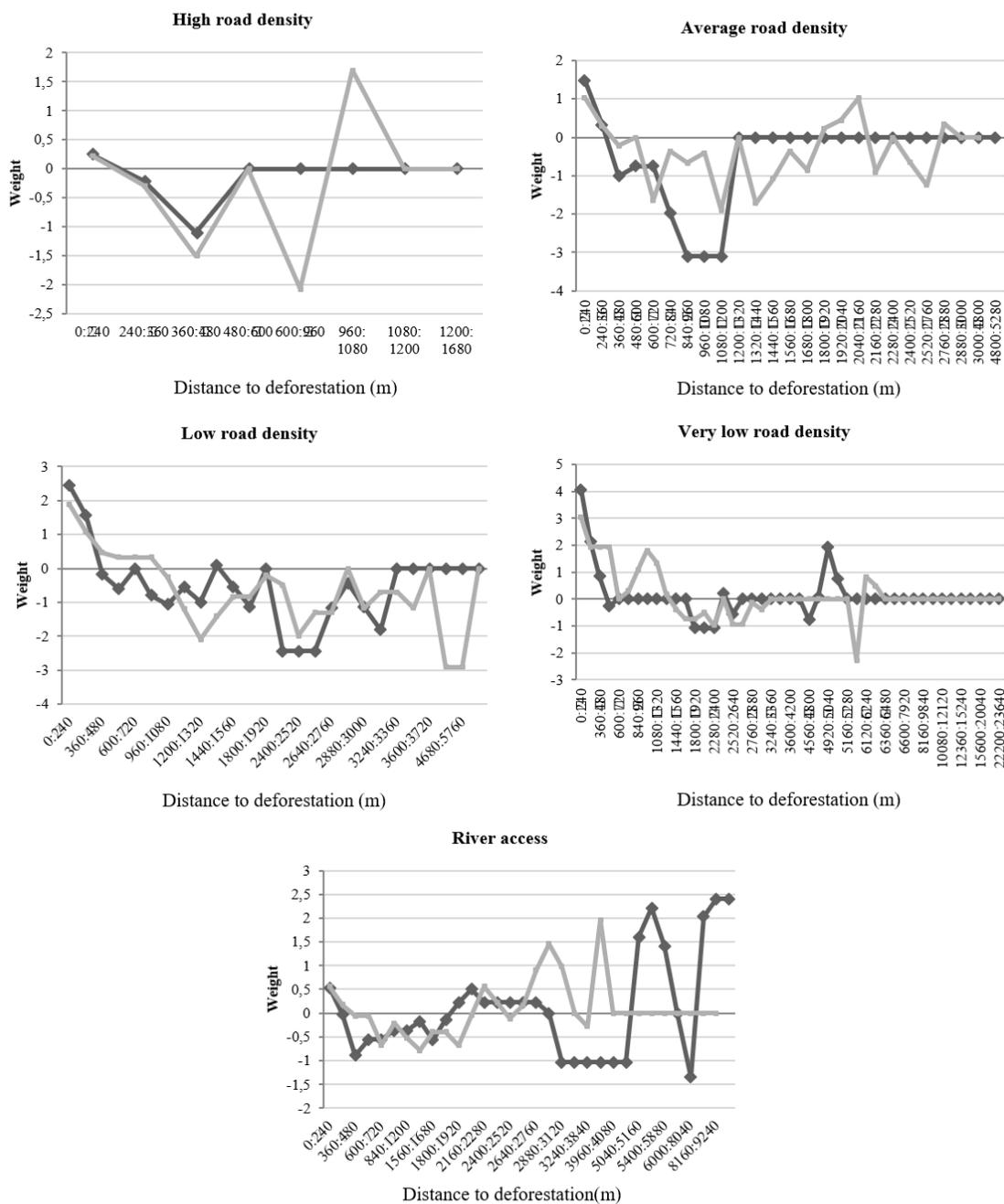
J



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 emergent 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.

Distance to deforestation

K



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

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

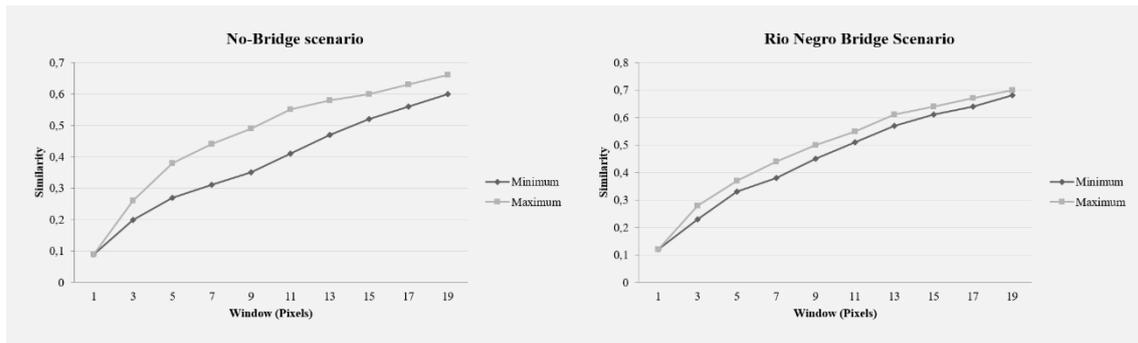


Figure S-7. Spatial validation of deforestation from the comparison between the observed map (Brazil, INPE 2017) and the simulated map for each scenario. Pixel (cell) width = 120 m. Legend: Maximum= more hits, or correct predictions; Minimum= fewer hits.

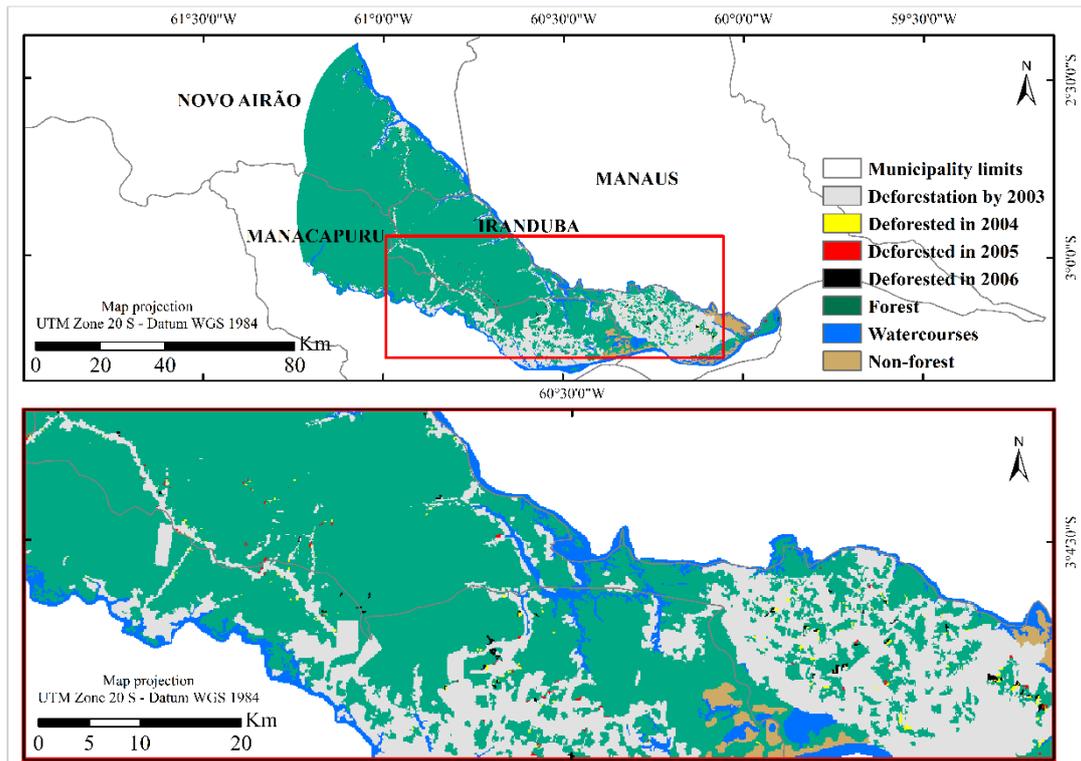


Figure S-8. Map of annual deforestation (Brazil, INPE 2017) for the period used to calibrate the No-bridge scenario (2004 to 2006).

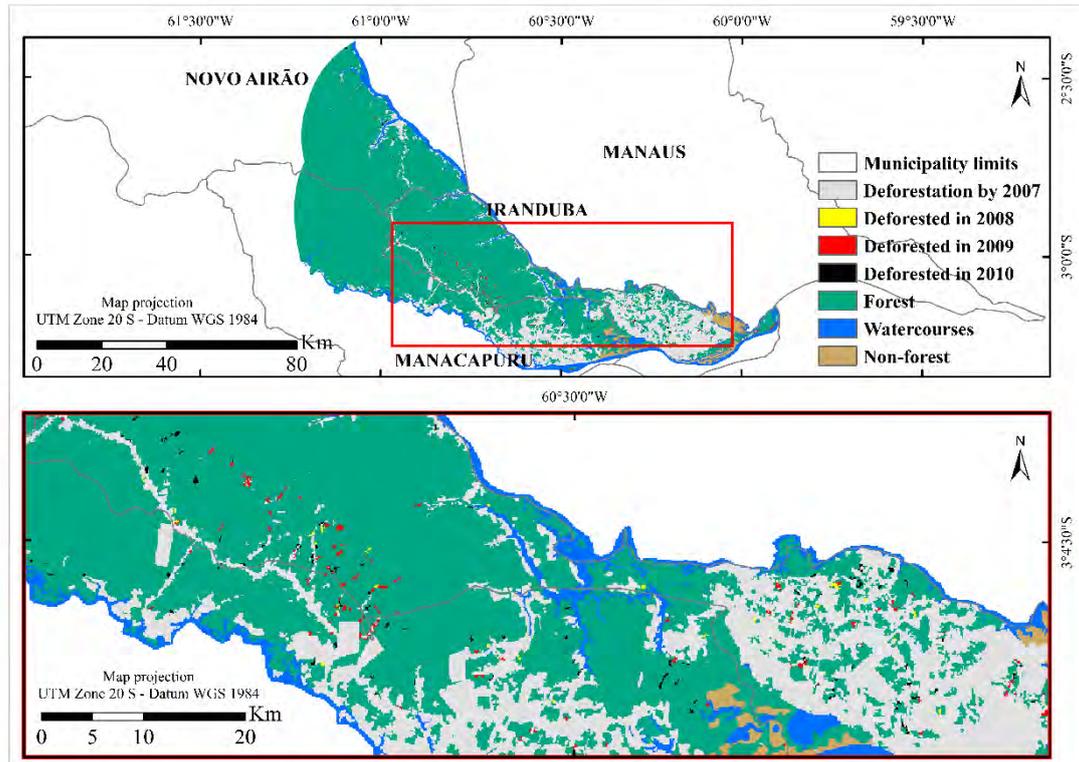


Figure S-9. Map of annual deforestation (Brazil, INPE 2017) for the period used to calibrate the Bridge scenario (2008 to 2010).

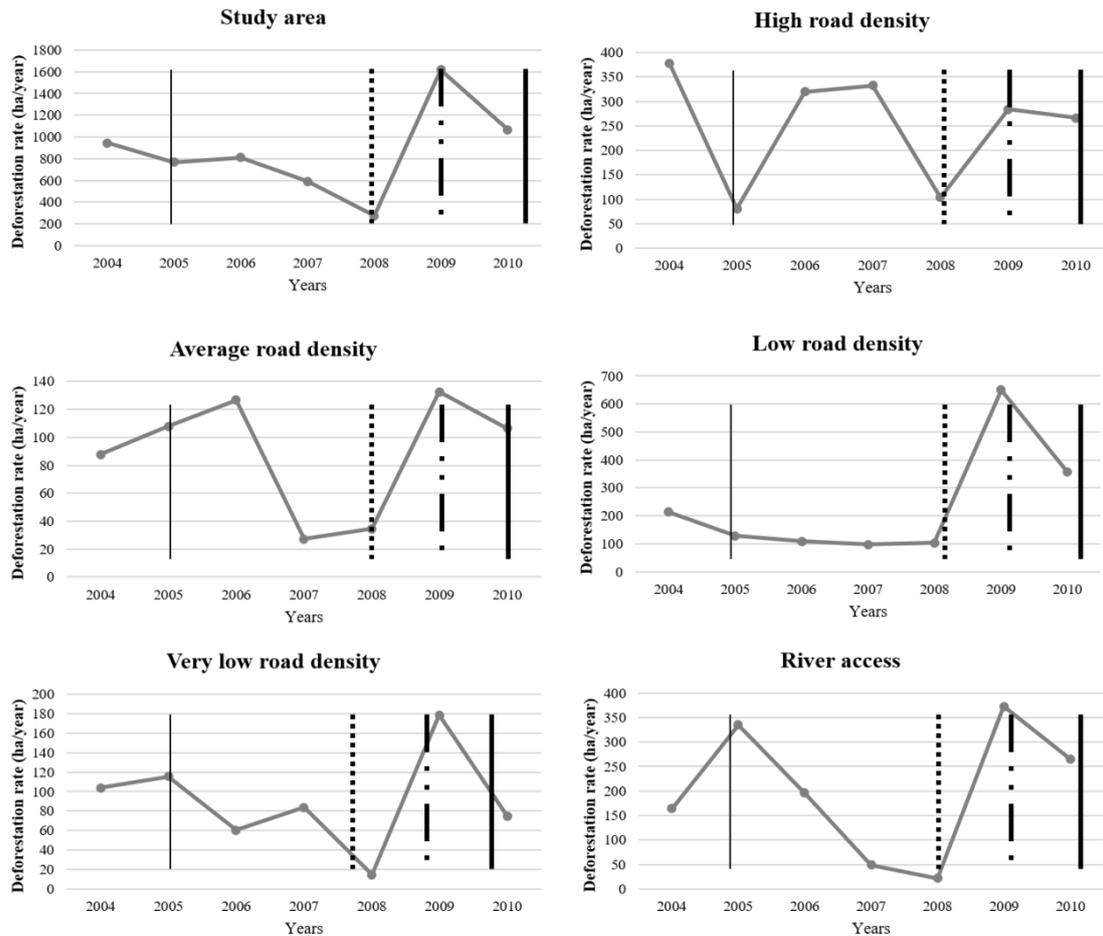


Figure S-10. Deforestation rate by region during the historical period based on data from Brazil, INPE (2017). In the early years, up to the thin line, there is a certain constancy in the deforestation rate. Between the thin line and the dotted line there is a tendency in the deforestation rate to decline 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.

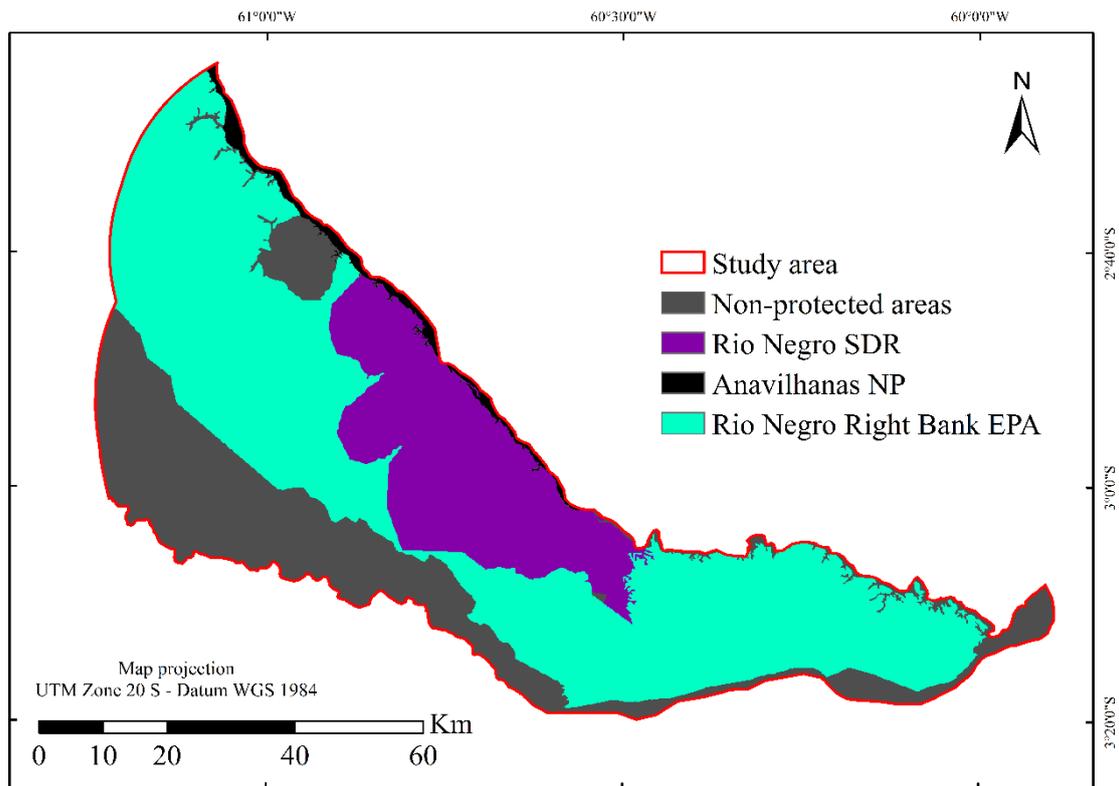


Figure S-11. Protected areas in the study area; data obtained from Brazil, MMA (2015). SDR – Sustainable Development Reserve; NP – National Park; EPA – Environmental Protection Area.

References

- Agterberg FP, Bonham-Carter GF (2005) Measuring the performance of mineral-potential maps. *Natural Resources Research* 14:1-17. <https://doi.org/10.1007/s11053-005-4674-0>
- Barni, P, Fearnside PM, Graça PMLA (2015) Simulating Deforestation and Carbon Loss in Amazonia: Impacts in Brazil's Roraima State from Reconstructing Highway BR-319 (Manaus-Porto Velho). *Environmental Management* 55(2):259-278. <https://doi.org/10.1007/s00267-014-0408-6>
- Beinroth FH (1975) Relationships between U.S. soil taxonomy, the Brazilian system, and FAO/UNESCO soil units. In Bornemisza E, Alvarado A (Eds), *Soil Management in Tropical America: Proceedings of a Seminar held at CIAT, Cali, Colombia, February 10-14, 1974*, North Carolina State University, Soil Science Department, Raleigh, North Carolina, U.S.A. pp. 97-108.
- Bonham-Carter GF, Agterberg FP, Wright DF (1989) Weights of evidence modeling: a new approach to mapping mineral potential. In Agterberg FP, Bonham-Carter GF (Eds), *Statistical Applications in Earth Sciences*. Geological Survey of Canada, Ottawa, Ontario, Canada. pp 171-183.
- Brazil, Projeto RadamBrasil (1976-1983) Levantamento de Recursos Naturais [Survey of natural resources]. Ministério das Minas e Energia, Departamento Nacional de Produção Mineral, Rio de Janeiro, RJ, Brazil. 36 vols.
- Brazil, IBGE (1992) Manual Técnico da Vegetação Brasileira [Technical manual of Brazilian vegetation] (Manuais Técnicos em Geociências no. 1). Fundação Instituto Brasileiro de Geografia e Estatística (IBGE), Rio de Janeiro, RJ, Brazil. 92 pp.
- Brazil, INPE (2017) Projeto PRODES - Monitoramento da Floresta Amazônica Brasileira por Satélite. Instituto Nacional de Pesquisas Espaciais (INPE), São José dos Campos, São Paulo, Brazil. <http://www.dpi.inpe.br/prodesdigital/> Accessed: 7 May 2017.
- do Prado H (2001) Solos do Brasil: Gênese, morfologia classificação e levantamento, 2^a ed. [Soils of Brazil: Genesis, morphology, classification and survey, 2nd ed.]. Sonopress, Piracicaba, SP, Brazil. 220 pp.
- Fearnside PM, Graça PMLA, Keizer EWH, Maldonado FD, Barbosa RI, Nogueira EM (2009) Modelagem de desmatamento e emissões de gases de efeito estufa na região sob influência da Rodovia Manaus-Porto Velho (BR-319) [Modeling deforestation and greenhouse-gas emissions in the region under influence of the Manaus-Porto Velho Highway (BR-319)]. *Revista Brasileira de Meteorologia* 24(2):208-233. <https://doi.org/10.1590/S0102-77862009000200009> [English translation available at: http://philip.inpa.gov.br/publ_livres/mss%20and%20in%20press/RBMET-BR-319_-engl.pdf].
- Macedo RC, de Almeida CM, dos Santos JR, Rudorff BFT (2013) Modelagem dinâmica espacial das alterações de cobertura e uso da terra relacionadas à expansão canavieira [Spatial dynamic modeling of changes in land cover and land use related to sugarcane expansion]. *Boletim de Ciências Geodésicas* 19(2):313-337.

- Santé I, García AM, Miranda D, Crecente R (2010) Cellular automata models for the simulation of real-world processes: A review and analysis. *Landscape Urban Plan* 96(2):108-122. <https://doi.org/10.1016/j.landurbplan.2010.03.001>
- Soares-Filho BS, Pennachin CL, Cerqueira G (2002) DINAMICA – a stochastic cellular automata model designed to simulate the landscape dynamics in an Amazonian colonization frontier. *Ecol Modelling* 154(3):217-235. [https://doi.org/10.1016/S0304-3800\(02\)00059-5](https://doi.org/10.1016/S0304-3800(02)00059-5)
- Soares-Filho BS, Rodrigues HO, Costa WL (2009) *Modeling Environmental Dynamics with Dinamica EGO*. Centro de Sensoriamento Remoto, Universidade Federal de Minas Gerais, Belo Horizonte, MG, Brazil. 115 pp. http://www.lapa.ufscar.br/geotecnologias-1/Dinamica_EGO_guidebook.pdf
- Vitel CSMN (2009) *Modelagem da dinâmica do desmatamento de uma fronteira em expansão, Lábrea, Amazonas*. Masters dissertation in tropical forest science, Instituto Nacional de Pesquisas da Amazônia (INPA), Manaus, Amazonas, Brazil. 121 pp. <http://bdtd.inpa.gov.br/handle/tede/2084>
- Yanai AM, Fearnside PM, Graça PMLA, Nogueira EM (2012) Avoided deforestation in Brazilian Amazonia: Simulating the effect of the Juma Sustainable Development Reserve. *Forest Ecology and Management* 282:78-91. <https://doi.org/10.1016/j.foreco.2012.06.029>
- Yeh AG-O, Li X (2006) Errors and uncertainties in urban cellular automata. *Computers, Environ and Urban Systems* 30:10-28. <https://doi.org/10.1016/j.compenurbsys.2004.05.007>