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Simulating deforestation and carbon loss in Amazonia: impacts in Brazil's Roraima state from reconstructing Highway BR-319 (Manaus-Porto Velho)

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ABSTRACT

Reconstruction of Highway BR-319 (Manaus-Porto Velho) would allow access from the "arc of deforestation" in the southern part of Brazil's Amazon region to vast blocks of forests in central and northern Amazonia. Building roads is known to be a major driver of deforestation, allowing entry of squatters and other actors. Rather than deforestation along the highway route, here we consider the road's potential for stimulating deforestation in a separate location, approximately 550 km north of BR-319's endpoint in Manaus. Reconstructing BR-319 has great potential impact to start a new wave of migration to this remote region. The southern portion of the state of Roraima, the focus of our study, is already connected to Manaus by Highway BR-174. We modeled deforestation in southern Roraima and simulated carbon emissions between 2007 and 2030 under four scenarios. Simulations used the AGROECO model in DINAMICA-EGO© software. Two scenarios were considered with reconstruction of BR-319 and two without this road connection. For each of the two possibilities regarding BR-319, simulations were developed for (1) a "conservation" (CONSERV) scenario that assumes the creation of a series of protected areas and (2) a "business-as-usual" (BAU) scenario that assumes no additional protected areas. Results show that by 2030, with BR-319 rebuilt, deforestation carbon emissions would increase between 19% (CONSERV) and 42% (BAU) above corresponding no- road scenarios.

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Introduction

Deforestation along the southern edge of Amazonia has advanced much faster than in other parts of the region due to the expansion and upgrading of the road network in the 1970s and 1980s (Fig. 1b). Roads allowed a large population of migrants to move to remote areas of the Amazon, and deforestation spread quickly (e.g., Perz et al. 2002; Pfaff 1999). In the mid-1980s, deforestation assumed alarming proportions with paving of major highways connecting Amazonia to São Paulo and other population centers in the South and Southeast regions of the country (Fearnside 1989; Oliveira 2005). Key developments included reconstruction of Highway BR-364 (Cuiabá-Porto Velho) and part of Highway BR-163 (Cuiabá-Santarem), allowing migrants to move to Amazonia. More recently, roads have facilitated arrival of soybeans, boosting agri-business on the southern edge of region (Carneiro-Filho 2005; Fearnside 2001, 2007).

[Figure 1 here]

Deforestation in Brazilian Amazonia has, until recently, been concentrated in the "arc of deforestation," a crescent-shaped strip along the forest's eastern and southern edges (Fig. 2). Low-input land uses such as extensive cattle pasture have now been joined in this part of Amazonia by more highly capitalized activities such as soybean cultivation. "*Grilagem*" (illegal appropriation of public land by large actors) and invasion of land by organized landless squatters ("*sem terras*") have continued to spread, especially in areas that are not yet part of the arc of deforestation. In addition, prices of commodities such as soybeans have strongly influenced the pace of deforestation (Barreto et al. 2008; Kaimowitz et al. 2004; Morton et al. 2006; Nepstad et al. 2006a). Deforestation rates in Brazilian Amazonia as a whole declined from 2004 through 2012, with yearly rates being closely correlated with commodity prices through 2008; thereafter rates and prices diverged when the decline in deforestation continued despite rising prices (Assunção et al. 2012; Barreto et al. 2011; Hargrave and Kis-Katos 2011). Among government control efforts that could explain the change in 2008, the most effective is believed to be the policy of Brazil's Central Bank introduced that year blocking loans from government banks to landowners with unpaid fines for environmental violations (BACEN Resolution 3.545/2008). Nevertheless, in 2013 deforestation rates in Legal Amazonia rose by 29% (Brazil, INPE 2014), and preliminary data indicate they rose further in 2014 (Fonseca et al. 2014).

[Figure 2 here]

The Brazilian government plans to build a series of infrastructure projects in Amazonia under its Program for the Acceleration of Growth (PAC). Among these is completion of the Jirau and Santo Antônio hydroelectric dams on the Madeira River upstream of Porto Velho (capital of Rondônia state) and reconstruction and paving of Highway BR-319 connecting Porto Velho to Manaus (capital of Amazonas state)

(Fearnside et al. 2009a; Viana et al. 2008). The construction phase of these dams has attracted approximately 100,000 people to Rondônia and may further exacerbate pressure on arable land there (Fearnside 2014). New forest lands are no longer available in the arc of deforestation and arable land is limited under Amazonian forest. Reopening Highway BR-319 would cause a new migratory flow from the arc of deforestation to central and northern Amazonia (Fearnside and Graça 2006; Viana et al. 2008). BR-319 was the main channel for migration to Roraima from 1975 until it was closed in 1988 due to lack of maintenance.

Migration to Roraima over the past decades has mainly been from people coming up the Amazon River by boat to Manaus and continuing on via Highway BR-174 to Roraima. This migration flow, plus that from Amazonas state (mostly from the Manaus area), would be little affected by opening Highway BR-319, in contrast to migration coming down the Madeira River from Rondônia. Of those arriving in Roraima from other states over the 1991-1996 period, only 5.2% came from states that would contribute to flows via BR-319, while 94.8% came from other states (Brazil, IBGE 2010). Migration flows from Amazonas state (5.9% of the 1991-1996 total moving to Roraima from other states) would be little affected. Other states with little expected effect are Maranhão (32.8%), Pará and Amapá (23.5%), Northeastern states other than Maranhão (12.7%), and the South and Southeast regions plus Goiás, Tocantins and the Distrito Federal (9.8%). The relatively small migration via the Madeira River is what would be transformed by opening BR-319, presumably in proportions similar to those in the 1991-1996 period. Of presumed Madeira-River migrants, 53.0% came from Rondônia, 12.9% from Acre, 22.8% from Mato Grosso and 11.3% from Mato Grosso do Sul. The percentage of migrants that BR-319 would bring from Rondônia may be higher, since some of the historical migration from Mato Grosso and Mato Grosso do Sul probably reached Roraima via the Amazon-River route.

Rondônia’s population more than doubled between the 1980 and 1991 censuses, with an annual net migration rate that was only surpassed by Roraima among the nine states in Brazil’s Legal Amazonia region (Fig.1a). Between 1991 and 2000 Roraima continued to experience strong net migration, while in the case of Rondônia the pattern reversed dramatically, with the state having a slight negative net annual migration rate, meaning that it had become a source of migrants (Perz et al. 2005, p. 33). Rondônia is a state with many settlement projects for small farmers. These areas begin with one family in each plot of land but soon enter a process where wealthier newcomers buy lots from the original settlers, often obtaining several lots in the names of different family members and managing the land as a medium or large cattle ranch (e.g., Fearnside 1984). For example, in the settlement at Apuí, in southern Amazonas state (an area where much of the current population has come from Rondônia due to road access from that state), as many as 38 lots are owned by a single family (Carrero and Fearnside 2011). The process of lot consolidation causes colonist families to sell their land and move to more-distant frontiers, both from the “push” of rising land prices in older settlements and from the “pull” of opportunities to obtain larger areas of cheap land elsewhere.

This process has been repeated on successive frontiers throughout Brazilian Amazonia over the past half century (e.g., Browder et al. 2008, Ludewigs et al. 2009). Its likely continuation guarantees a source of future rural-to-rural migration. Migration in Brazil is generally rural-to-rural, rural-to-urban or urban-to-urban, but not urban-to-rural. In Rondônia, hotspots of migration spring up regularly, with many migrants arriving from other parts of the state in response to rumors of available land (Caviglia-Harris et al. 2013). The currently rumored El Dorado among farmers in Rondônia is “Realidade,” which is a spontaneous settlement located in Amazonas state near the northern end of the passible portion of Highway BR-319 (personal observation). If BR-319 were to be opened to traffic all the way to Manaus, it is likely that southern Roraima would suddenly take on the role of rumored paradise for land-seekers in Rondônia. Those who respond to the opportunity of newly opened areas include both those who sell land in older settlements and those who have no land**.** Organized landless farmers (*sem terras*) represent a significant factor in population movements in Amazonia (Perz et al. 2010; Simmons et al. 2010).

Southern Roraima has over 70,500 km^2 of primary forests (Supplementary Online Material) that are accessible from Manaus via Highway BR-174 (Manaus-Boa Vista). The region could attract much of the migratory flow that is expected if BR-319 is reconstructed. Low land prices compared to those in the arc of deforestation and more fertile soil as compared to the Manaus area are strong attractions. Low population density represents an additional attraction: as of 2010, Roraima had only 451,000 inhabitants, of whom 284,000 (63%) were living in the capital city of Boa Vista (Brazil, IBGE 2013a). This equates to an average density of 2 inhabitants per km^2, but density falls to 0.7 inhabitants/km^2 if the capital city is excluded. In addition, Roraima is located in the far north of the country, thereby providing comparative advantages such as access to external markets via ports in Venezuela and Guyana.

These facts could cause increases in deforestation and environmental degradation, as shown by a similar case in the recent past resulting in a large influx to Roraima. In the period between 1995 and 1997 a total of 23 settlement projects was created in Roraima (Brazil, INCRA 2007). Of these, 16 are in the southern portion of the state where they have attracted more than 50,000 migrants from other parts of Brazil (Brazil, IBGE 2008; Diniz and Santos 2005). The settlements were established as part of a state government effort to recover population after a halting of gold mining in 1990 caused loss of inhabitants (AMBITEC 1994; Diniz and Santos 2005). Part of the advance of settlement projects was due to paving Highway BR-174 and part from paving BR-210 (Northern Perimeter Highway) over the 1995-1997 period. These highways served as access routes to newly created settlement projects and for transport of products to markets in Manaus and Boa Vista (Fig. 2, part 1).

The effect of Amazonian roads on deforestation is not a mere theoretical possibility: it has been demonstrated in studies linking road construction and deforestation increase with increasing migration (e.g., Laurance et al. 2001; Sawyer 1984; Soares-Filho et al. 2004). Since Roraima is located at the "end of the chain" of migration (imagining links of a chain connecting the arc of deforestation to Roraima), relatively few migrants have arrived as compared to points that are closer to the migration source. This has caused a sort of "repressed demand" in Roraima, and reopening BR-319 could make the stronger migration wave move to the end of the chain. Moreover, measures to curb deforestation from BR-319, such as creation of protected areas, are limited to the strip along BR-319 itself (e.g., Fearnside et al. 2009a).

Our goal in the present paper is to examine effects on deforestation in southern Roraima in what is likely to be a critical case in Brazil’s development plans for Amazonia. We simulate deforestation under four scenarios between 2007 and 2030 and estimate resulting carbon emissions. The environmental impact study for reconstructing Highway BR-319 gives no consideration to impacts beyond the strip on either side of the road between Porto Velho and Manaus (UFAM 2009; see Fearnside and Graça 2009). Ignoring effects beyond what government authorities define as the "region of direct impact" is a generic problem in environmental impact assessment and licensing in Brazil and elsewhere. Our research is intended to answer the question of what effects re-opening Highway BR-319 could have on deforestation and loss of other original vegetation in southern Roraima. Effects stem from migrants continuing their journeys beyond the end of BR-319, which terminates in Manaus, Amazonas, approximately 550 km to the south of the study area. We also consider the extent to which creating additional protected areas might reduce forest loss in the study area.

Methodology

Study Area

Our study area encompasses five municipalities in southern Roraima: Caracarai, Rorainópolis, São Luiz do Anauá, São João da Baliza and Caroebe, with an area of 98,955 km², or 44.1% of the total area of Roraima (Fig. 2**)**. The region is crossed from north to south by Highway BR-174 and from east to west by Highway BR-210. Southern Roraima had 60,980 inhabitants in 2007, approximately 48% of whom were living in the countryside (Brazil, IBGE 2010). Cumulative deforestation totaled 3723 km² by 2007, representing 3.7% of the total area of southern Roraima and about 5% of the remaining forest areas in this part of the state (Brazil, INPE 2014). Southern Roraima includes the Jauaperi National Forest (FLONA) and the Wai-Wai Indigenous Land (Fig. 2).

Model Rationale, Implementation and Testing

The AGROECO Model

To simulate deforestation and to create future scenarios we used the AGROECO model developed by Fearnside et al. (2009a) in DINAMICA-EGO software (Soares-Filho et al. 2002, 2014). Each iteration of the AGROECO model creates an area of accessible forest (Fig. 3). Accessible forest is a buffer around existing roads and previous clearings. Accessible area and subsequent deforestation expand as new roads are built by the software's road-building module (Supplementary Online Material). The accessible forest surface is composed of a strip of pre-defined width (2 km in this case) on each side of all roads built in the model. In AGROECO, unlike demand-driven models, the amount of deforestation (and not only its location) responds to presence of transportation infrastructure (Fearnside et al. 2009a; Yanai et al. 2012).

[Figure 3 here]

Schedule of Planned Roads

In all study scenarios, major roads were built according to the government of Roraima's official road-paving timeline. Secondary roads were mapped using the multiple criteria evaluation (MCE) tool in DINAMICA-EGO. Probable dates for constructing main roads were based on official plans (Brazil, Ministério da Defesa *C*. 2001, pp 75-76; Roraima 2009). Planned roads totaled 867 km, making 1,040,400 ha of forest available for deforestation during the simulations (Table 1).

[Table 1 here]

Static and Dynamic Variables

Static variables are factors that do not change in value over the course of a simulation. We used maps of altitude (Brazil, SIPAM 2008), slope (derived from SRTM data: Brazil, EMBRAPA 2013), soils (Brazil, IBGE 2013b; Brazil, Projeto RADAMBRASIL 1973-1983) and vegetation (Brazil, IBGE 2013b; Brazil, Projeto RADAMBRASIL 1973-1983). We also used maps of indigenous lands and conservation units (Brazil, IBGE, 2013b), rivers (Brazil, SIPAM 2008), settlement projects (Brazil, INCRA 2007) and the initial (1998) network of major and secondary roads (Brazil, SIPAM 2008; updated by the authors to 2007 from LANDSAT-TM images).

Dynamic variables are those whose values change over the course of a simulation. These included distance to major roads and distance to secondary roads (new major roads are built according to an official schedule and construction of endogenous secondary roads is simulated in the model). Other dynamic variables were distance to available land, distance to deforestation and distance to forest, distance to settlement projects and distance to indigenous lands and conservation units (affected by changes in the status of land as a settlement project or as a conservation unit).

Historical deforestation data were used to test the model's efficiency in allocating deforestation to sites where it is most likely to occur (depending on factors that promote or inhibit clearing). We also tested the model's performance in not allocating deforestation to locations where it has little or no likelihood of occurring (infertile soils, hill tops, flooded areas, and areas far from road infrastructure) (Barni 2009).

Spatial Data Input to the Model

The model uses as input data land-use maps based on LANDSAT-TM satellite images for 2004 and 2007 (Fig. 4). Maps of weights of evidence and of transition probabilities are calculated from these maps to calibrate the model (Supplementary Online Material). In the case of categorical variables, coefficients of weights of evidence are calculated from the vulnerability or lack of vulnerability of each class to deforestation. For classes favorable to deforestation, the model assigns positive coefficients, while classes that are not favorable receive negative coefficients. In the case of continuous variables, the model creates bands of distances from the variable of interest (for example roads) and assigns coefficients of weights of evidence for each distance range according to favorability for deforestation.

[Figure 4 here]

Weights of Evidence

Weights of evidence are based on the Bayesian conditional probability method (Supplementary Online Material). In modeling dynamics of land-use and land-cover change, weights of evidence are applied to calculate *a posteriori* probabilities. In the case of deforestation, we have *a priori* knowledge of locations with conditions that are favorable to deforestation. Land-use maps and the static and dynamic variables were combined in this modeling step in a DINAMICA-EGO sub-model for calculating weights of evidence (Fig. 5). For example, the transition probability for a given cell "*i*" changing from one state (e.g., forest) to another (e.g., deforestation) over a period of time is evaluated as a function of its distance to deforestation or to the forest edge and distance to the road network. Probability of transition of a cell "*i*" is also evaluated in terms of its location when it is tested in relation to static variables such as soil type and initial vegetation.

[Figure 5 here]

In each iteration (representing a year), all model cells are examined or tested with respect to all variables; all odds are cumulative. Depending on its location and variable values favoring deforestation, a cell's transition probability can increase. A cell located far from a road network and from deforestation has decreased transition probability.

Weights of evidence can be either positive (favoring deforestation) or negative (inhibiting deforestation). Weights of evidence are recalculated in each iteration; they consider total available forest area resulting from incorporating newly created roads into the current road network. Major roads are scheduled to be built at predetermined steps or iterations of the simulation (Table 1).

Patcher and Expander Functions

DINAMICA-EGO uses local rules for its cellular automata transition algorithm mechanism, which is composed of two complementary functions: "Patcher" and "Expander" (Supplementary Online Material). The Patcher function searches for cells around a site chosen for a transition and forms new patches of deforestation through a seeding mechanism. This is done first by choosing the central cell of a new patch of deforestation and then selecting a specific number of cells around the central cell according to its transition probability P ($i \rightarrow j$), calculated from weights of evidence. The Expander function causes expansion of pre-existing patches of a given class such as deforestation. In Expander a new spatial transition probability P ($i \rightarrow j$) depends on cell numbers of type "*j*" around a cell of type "*i*". For building scenarios we used the following transitions: forest to deforestation ($3 \rightarrow 1$), deforestation to regeneration ($1 \rightarrow 2$) and regeneration to deforestation ($2 \rightarrow 1$).

Scenario Assumptions

In simulating deforestation, two scenarios were considered when assuming no reconstruction of Highway BR-319. The first scenario is "business as usual," called "BAU1"; it is used as a baseline simulation. The second is a "conservation" scenario called "CONSERV1"; it assumes establishment of conservation areas. Additionally, two similar scenarios ("BAU2" and "CONSERV2") assumed reconstruction of Highway BR-319 in 2011, an officially announced start date that has since been delayed**.** Scenario assumptions are summarized in Table 2.

[Table 2 here]

Proposed Conservation Units and Planned Roads

Deforestation containment policies were simulated in both conservation scenarios: CONSERV1 (without BR-319) and CONSERV2 (with BR-319). To this end, scenarios were simulated with creation of three conservation units; in these scenarios any planned roads that would have had destinations inside these conservation units were withdrawn from the model. Conservation units proposed in the conservation scenarios totaled approximately 695,000 ha. Shapes and locations of conservation units were planned to enable connectivity with existing conservation units (Ferreira and Venticinque 2007). As an imposition of the model there is no deforestation inside proposed conservation units during simulations. Conservation units that already existed at the beginning of the simulation have further construction of endogenous roads blocked within their borders, thus reducing but not totally eliminating deforestation in these units.

Three conservation units were proposed because three large deforestation fronts were detected threatening these blocks of intact forest (Fig. 6). Each conservation unit was designed to encompass all of a threatened forest block in order to contain future deforestation threats. Proposed conservation units were designed so that they would fit into the set of protected areas that were already present (indigenous lands, national forests and biological reserves).

[Figure 6 here]

Calibrating the AGROECO Model

The AGROECO model was calibrated from calculations of forest-to-deforestation transition rates derived from PRODES land-use maps for the study area from 2004 and 2007 (Brazil, INPE 2014). BAU1 was considered to be a baseline and served as a reference for other scenarios. This followed historical deforestation rates for southern Roraima (Barbosa et al. 2008).

Calculation of transition rate is done according to Equation (1):

$$\text{Basic annual rate} = ((\text{Deforestation}_{(2007)} - \text{Deforestation}_{(2004)})/\text{Forest}_{(2004)})/3 \quad (1),$$

where "basic annual rate" is derived from land-use maps from 2004 and 2007.

The basic annual rate was multiplied by the annual rate of planned road building in iterations where construction of roads was scheduled. Calculation of the annual rate of planned road building is given by Equation 2:

$$\text{Annual rate of planned road building} = (AAFFR_t/AAF_{(t-1)}) + 1 \quad (2),$$

where: $AAFFR_t$ is "area of available forest from roads" at time "t" and $AAF_{(t-1)}$ is "area of available forest" at time "t-1".

The annual rate of planned road building reflects an increase in the probability of deforestation in subsequent iterations as a result of a road being built. This is due to the assumption of increasing human pressure on this accessible area. This rate was used in all scenarios in iterations with planned roads.

For BAU2 and CONSERV2, both of which assume reconstruction of BR-319 in 2011, a “migration factor” was used in addition to the rates described for scenarios without BR-319. Subsequent postponements have delayed the officially programmed 2011 reconstruction date, but model results apply equally well to the period after reopening BR-319 whenever it occurs. The model’s migration factor (Equation 3) simulated increased deforestation by expected migrants to the region after rebuilding BR-319:

$$\text{Migration factor} = DRSP_{(95/97)}/\text{Basic annual rate} \qquad (3),$$

where: $DRSP_{(95/97)}$ is “deforestation rate in settlement projects” for those projects created between 1995 and 1997. This rate is derived from observed deforestation in southern Roraima between 1996 and 2001, which represents the period after creating the settlement areas in question. “Basic annual rate” is that calculated by Equation 1.

Donating land and creating settlement projects by the state government during this period stimulated a large migratory flow to southern Roraima (Brazil, IBGE 2008; Diniz and Santos 2005). The calculated migration factor was three and was applied from 2013 onwards. We assumed that road construction serves as infrastructure providing access to land in settlement projects; this process increases deforestation (Alves et al. 1992; Brandão Jr. and Souza Jr. 2006).

Rate calculations presented above were performed in a non-spatial numerical model using Vensim® software (Ventana Systems, Inc. 2012). Resulting values were made available in the corresponding iteration of the DINAMICA-EGO model through a lookup table (Soares-Filho et al. 2004). In each iteration, rates were calculated in the Vensim model. Rates are passed to the AGROECO spatial model (in the 32-bit version of DINAMICA-EGO) via a link coupling these two models to obtain deforestation for that year (Fearnside et al. 2009a).

Validating the AGROECO Model

Validation compared maps of simulated deforestation from 2004 to 2007 in the baseline scenario with observed deforestation in 2007 (Fig. 7). We used the fuzzy method (Hagen 2003) as modified by Soares-Filho et al. (2014), which uses an increasing number of cells in "windows" (5 × 5 to 31 × 31 cells) applied to the maps. This method considers similarity index values ≥ 50% sufficient for model validation. The similarity index value obtained was 54.7% for our simulation model in a window of 7 × 7 cells.

[Figure 7 here]

Impact on carbon emissions

Estimation of Original Vegetation Biomass

To estimate emissions one must know carbon stocks in original vegetation biomass. For forest ecosystems, below-ground and above-ground carbon stocks (excluding soil carbon) were taken from the map of biomass density in Amazonia developed by Nogueira et al. (2008) using RADAMBRASIL inventories (Brazil, Projeto RADAMBASIL 1973-1983). For two non-forest ecosystems ("*campina*" and savanna), we used studies by Barbosa and Ferreira (2004) and Barbosa and Fearnside

(2005). For root biomass estimation in non-forest ecosystems we used a root/shoot ratio of 2.81 (R.I. Barbosa pers. comm.; see Barbosa et al. 2012). Calculations were done as map-algebra operations in ArcGis software using the average density of biomass for each map class and the map of land use in 2007. To obtain areas occupied by each forest type, a multiplication was performed between a binary map of forest classes (Class 1) and the map of biomass classes (Classes 1 to 15). The totals of these areas were obtained by summing the number of pixels in each class and multiplying by the area of each pixel (6.25 ha). Total amount of biomass remaining in southern Roraima in 2007 was obtained by summation of the area (ha) occupied by each forest type multiplied by its respective average biomass in megagrams (tons) per hectare (Mg ha^{-1}). These estimates of above- and below-ground biomass (including necromass) were then converted to carbon stocks (Table 3).

[Table 3 here]

Estimation of Secondary Vegetation Biomass

For estimation of secondary vegetation biomass simulated in the scenarios for 2030 we used the method developed by Fearnside and Guimarães (1996). Composition of simulated secondary vegetation in annual landscapes was determined taking into account the relative abundance of secondary forests in 2030. This was calculated based on residence time for secondary vegetation cells in the landscape (Almeida et al. 2010). Rates for clearing secondary vegetation and for regrowth used for the scenarios were 22% and 4.5%, respectively (Ferraz et al. 2005; Soares-Filho et al. 2004). Simulated secondary vegetation was added to other types of land cover to form the replacement landscape; at the end of the simulation in 2030 the landscape was 75.6% pasture, 9.3% agriculture and 15.1% secondary forest.

Estimation of Carbon Emissions

Forest biomass was converted to carbon using a conversion factor of 0.485 (Silva 2007). For the deforested area, the carbon content of secondary vegetation biomass used in calculating carbon stock in the equilibrium landscape was considered to be 45% of the dry weight (Fearnside 1996, 2000). Thus:

$$\text{Tons } C_{(forest)} = \text{Tons forest biomass} \times 0.485 \quad (4),$$

where “tons $C_{(forest)}$” is estimated carbon contained in biomass in tons (Mg); “Tons forest biomass” is total biomass (oven-dry weight) found in forest.

$$\text{Tons } C_{(sec.\ veg.)} = \text{Tons secondary vegetation biomass} \times 0.450 \quad (5),$$

where “Tons $C_{(sec.\ veg.)}$” is estimated carbon contained in biomass in tons (Mg); “Tons secondary vegetation biomass” is total dry weight of biomass found in secondary vegetation.

Emissions estimates for each scenario generated by deforestation up to 2030 were calculated from the loss of carbon stocks in forests that were present in 2007, after deducting carbon in replacement vegetation. Thus, following Fearnside et al. (2009b), net carbon emission is given by:

$$\Delta C_{(Scenario)} = A \times (C_{2030} - C_{2007}) \quad (6),$$

where: "$\Delta C_{(Scenario)}$" is net carbon emission (MgC) from deforestation between 2007 and 2030 for each scenario, after deducting the average carbon stock in the landscape that replaces forest (cf, Fearnside 1996); "A" is area (ha) deforested during the period; "C_{2007}" and "C_{2030}" represent the carbon stocks in the landscape in Mg in 2007 and 2030.

Our carbon emission estimates only include emissions from clearing forest biomass, minus uptake by biomass in the replacement landscape. The estimates exclude changes in soil carbon stocks and losses to forest degradation from logging, fire and climate change impacts. Ecophysiological processes are excluded, as are the carbon-equivalents of trace-gas emissions.

Results and Discussion

Model Validation

"Validation," or comparison of model behavior with real-world observations, provides essential information for judging the realism of modeled results. We validated our model through simulation runs between 2004 and 2007 using as inputs the 2004 land-use map and the calibration parameters for BAU1 (without BR-319). The model-generated 2007 map was compared with the land-use map for 2007 provided by the National Institute for Space Research (Brazil, INPE 2014). The comparison used the reciprocal similarity technique (Soares-Filho et al. 2014). Importantly, this approach makes comparisons of maps of differences, i.e., maps of simulated deforestation in a period and not of cumulative deforestation (Soares-Filho pers. comm.).

No general rule exists for calibration and validation of models (Mazzoti and Vinci 2007). Validation should demonstrate that a model has, within its domain of applicability, a satisfactory range of accuracy consistent with the model's intended application. This demonstration shows that the model would be suitable for use in a particular context but, by itself, does not mean that this is the best model (Rykiel 1996). Validation continues to be subject to a variety of different approaches: "There is not, and never will be, a totally objective and accepted approach to model validation" (McCarl 1984).

Biomass and Carbon Sequestration by Simulated Secondary Vegetation

The percentage of secondary vegetation derived from degraded pasture in our simulated landscapes (15.1% of total area deforested) is similar to the percentage (13%) found by Ferraz et al. (2005) under future scenarios in Rondônia. In an estimate for Amazonia as a whole in 2003, Ramankutty et al. (2007) used a Markov matrix to calculate that secondary vegetation occupied approximately 32% of the total area deforested. Recent studies applying remote-sensing techniques estimate that this type of vegetation occupies between 19 and 28% of the deforested portion of Brazilian Amazonia (Almeida et al. 2010; Carreiras et al. 2006; Neeff et al. 2006). Close agreement of our results with data in the literature suggests that this methodology can be used in future work to model dynamics of land-use and land-cover change to obtain more "realistic" and reliable estimates of carbon in deforested landscapes.

Cumulative Deforestation under the Four Scenarios

Figure 8 shows evolution of cumulative deforestation under the four scenarios. Curves representing increase of deforested areas under BAU1 and CONSERV1 scenarios without BR-319 have constant linear evolution over time, similar to what is observed in Roraima currently (Barbosa et al. 2008). In Figure 8 one also notes a strong increase under BAU2 and CONSERV2 deforestation scenarios due to application of a migration factor in the simulation model beginning in 2013, with the rate of increment stabilizing after 2020.

[Figure 8 here]

BAU1 (baseline scenario) projects historical evolution of deforestation in the region. Planned construction of major roads and appearance of endogenous secondary roads (which is automatic in the model) cause area deforested to almost double in extent, with a 92% increase between 2007 and 2030 (372,250 ha versus 715,250 ha).

BAU2 (with BR-319) shows a possible trajectory, in time and space, of the roads that are preconditions favorable to deforestation. These conditions, combined with probable migratory flow to Roraima provoked by re-opening BR-319 in 2011, are simulated in the model by applying deforestation rates similar to those observed in settlement projects in the recent past in Roraima. These rates were only applied over a short time span (2013-2018) following a schedule of opening planned roads in the future. Under this scenario, reconstruction and paving of BR-319 occurs in 2011, and cumulative deforested area reaches 486,000 ha by 2030 -- an increase of 130.4% (Table 4). The delay in reconstructing BR-319 can be expected to postpone these increases in deforestation in Roraima by an equivalent number of years.

[Table 4 here]

In CONSERV1 and CONSERV2 (without and with BR-319) an increase in deforestation occurred throughout the area accessible via the pre-existing road network, which is where the settlement projects are located (Figs. 9c and d**)**. This indicates that there would be an intensification of land use in these locations in response to simulated conservation units having restricted forest availability for clearing elsewhere. CONSERV1 was the scenario with least deforestation, with cumulative area deforested reaching 654,513 ha in 2030, or a 75.6% increase over that in the initial landscape in 2007.

[Figure 9 here]

In the CONSERV2 scenario (with rebuilding Highway BR-319)**,** cumulative deforested area reached 775,888 ha in 2030, an increase of 108.2% over the deforested area in the initial landscape in 2007. In spite of its being a conservation scenario, this scenario deforested 17.7% more than the baseline scenario without BR-319 (BAU1). In both conservation scenarios an increase occurred in invasion of Jauaperi National Forest. This was more intense in CONSERV2, indicating that the national forest (FLONA) had become an area of high anthropogenic pressure and was acting as a "safety valve" for deforestation.

In the conservation scenarios, both in general and due to proposed conservation units, a pattern of deforestation developed that was more homogeneous and "compact," resulting in a landscape that was less fragmented by deforestation than was the case under the two BAU scenarios. In both conservation scenarios there was a greater "saturation" by deforestation. This was observed in our simulations along Highway BR-174 and in the Anauá Directed Settlement Project near the Rorainópolis municipal seat and also along Highway BR-210 and on side roads near the municipal seat.

Effect of Planned Roads on the Deforestation Pattern in Simulated Scenarios

Although both business-as-usual scenarios (BAU1 and BAU2) used the same construction schedule for planned roads, in BAU2 (with BR-319) we used a migration factor to simulate a more vigorous deforestation increase after 2012. Thus, the shape and the spatial distribution of deforestation in the two scenarios were similar, the difference being in intensity of deforestation. BAU2 deforested 38.4% more than BAU1, and CONSERV2 deforested 32.8% more than CONSERV1. The fact that CONSERV2 (with BR-319) deforested 17.7% more than BAU1 (without BR-319) does not mean that creating reserves is ineffective. Rather, it reflects the severity of the effect of opening a road like BR-319 in terms of future deforestation in a region with low governance, such as southern Roraima (e.g., Barni et al. 2012).

In general, planned roads accelerated deforestation for the simulated BAU scenarios, as has been the predominant pattern when highways are opened in Amazonia (Escada and Alves 2001; Nepstad et al. 2001; Soares-Filho et al. 2004, 2006). Planned roads leading to blocks of forest north of the Jatapú hydroelectric dam (years 2014 and 2015) and to forest near the Branco River in the Caxias Settlement Project in Caracaraí municipality (years 2012 and 2015), increased local deforestation. The same effect was also seen east of Highway BR-174 (2011) in the Ecuador Settlement Project (Figs. 9A and B).

The opposite effect, or deforestation failing to accompany planned road construction, was seen along some roads. This occurred in BAU1 (without BR-319) along the planned road that would penetrate the forest block to the west of the Wai-Wai indigenous land (2013) as well as in Caracarai municipality and to the west of the Anauá Directed Settlement Project (2013). This effect also occurred in both scenarios on the road linking the Jauaperi River to Santa Maria do Boiuçú (2018) in Rorainópolis municipality. In the case of the first two roads, this fact could be related to proximity of conservation units, low soil quality and little prior deforestation. These factors decrease probability of deforestation in the simulations. Along the access road to Santa Maria do Boiuçú, which crosses the Jauaperi River, low deforestation could be explained by unfavorable terrain because this is in an area subject to seasonal flooding (Fig.10).

[Figure 10 here]

Deforestation Processes

Likelihood of deforestation evolving continuously in southern Roraima at rates similar to those observed currently without BR-319 is strengthened by the great availability of forest areas to clear. Invasions of public land by squatters (*posseiros*) and large land thieves (*grileiros*), illegal logging, high turnover of owners in settlement projects and widespread advance of pasture over other forms of land use are already present in southern Roraima (Barni et al. 2012). These are factors that contribute to uncontrolled deforestation and environmental degradation (Fearnside 2008; Soares-Filho et al. 2004). These facts alone would justify creating environmental-protection areas (Ferreira et al. 2005; Nepstad et al. 2006b; Soares-Filho and Dietzsch 2008; Soares-Filho et al. 2010). This would be true even without reconstruction of BR-319, as shown in CONSERV1 (without BR-319).

Considering the origin of actors who could arrive by road (Fearnside 2008; Soares-Filho et al. 2004), their ability to destroy forest is greater than that of most migrants attracted to Roraima in the recent past (Mourão 2003). This means that we are conservative in assuming constant per-capita contribution to deforestation as indicated by historical patterns in southern Roraima. We believe that the model was adequate to represent advance of deforestation in the study area over the time period of our analysis. We emphasize that this is not a simple extrapolation of rates of deforestation, but involves several underlying factors with different levels and scales (e.g., Brondizio and Moran 2012; Foley et al. 2007; Ludewigs et al. 2009). It reflects the assumption of several factors acting simultaneously in decisions of actors, for example concerning how much area to deforest annually, where to deforest (favorable sites in terms of soil fertility, slope, etc.), when clearing occurs (as influenced by the schedule for building road infrastructure), cutting secondary forest, pasture maintenance, etc. It also assumes migratory movement (e.g., Soares-Filho et al. 2004), simulates the government's deforestation-containment policies (creating conservation units) (e.g., Yanai et al. 2012) and the opening of secondary roads that directly influence these rates (e.g., Fearnside et al. 2009a). The model incorporates a wide range of land-use determinants and recognizes that spatial distribution of population, opening of roads and land-use change are determined jointly and are supported by an economic framework (e.g., Campari 2005; Chomitz and Gray 1996).

While the precise course of future deforestation in Roraima if BR-319 is rebuilt is inherently uncertain, past induced migratory responses are sufficiently documented empirically that the deforestation in our simulated scenarios could well be what plays out in practice. Since the environmental impact study for BR-319 focused only on the roadside, thus assuming away any impacts in Roraima, our scenarios offer a far better basis for cost/benefit evaluation than does the official scenario. This matters not only for the road decision but also for decisions about complementary options for protected areas.

Viewed in this light, our results may be seen in a framework like the one that has long surrounded contingent valuation methodologies for assessing environmental value: nobody argues they are perfect but many argue they are more useful than assuming a value of zero. In other words, our scenarios should not be viewed as what 'will happen,' but instead as showing that 'things like this could happen but are being assumed away, and thus should be considered.' Such a framing is not surprising for a dynamic analysis considering indirect effects, which are harder to study empirically than are tightly bounded analyses of impacts of more limited scope. Tightly bounding analyses can appear to be "more accurate," which in one manner of speaking is correct, but, in a larger scope they can actually produce less insight (Pfaff and Robalino 2012). Looking ahead to consider when the world will not be like today is valid as an input for policy making.

Resistance of Reserves to Invasion

The model assumption is that conservation units effectively deter deforestation. While reserve invasions do, in fact, occur in Amazonia, we believe that this assumption is reasonable for the simulated period. A key factor justifying a no-deforestation assumption is that the simulated reserves were created without any prior deforestation inside their borders (e.g., Soares-Filho et al. 2010; Vitel et al. 2009). Where this is not true, deforestation likelihood is much greater. For example, some deforestation occurred in our simulation in Jauaperi National Forest (FLONA) during the 2004-2007 period because previous historical deforestation occurred in and around this conservation unit.

Biomass and Carbon Emission in Simulated Scenarios

Simulated carbon emissions reached 56.4 × 10^6 Mg in 2030 (Table 4) under BAU1 (without BR-319), which represents continuing current deforestation patterns under expected conditions in southern Roraima. Assumptions of BAU2 (with BR-319) led to high biomass carbon loss: 86.4 × 10^6 Mg of biomass carbon were lost by the end of a 23-year simulation. Considering biomass regrowth in replacement vegetation, this gross loss corresponded to net committed emissions (Fearnside 1997) of 80.3 × 10^6 Mg of carbon.

Carbon loss differences between BAU1 and BAU2, representing the effect of reconstructing BR-319, totaled 23.9 × 10^6 Mg of carbon at the end of 23 years. This equals approximately five years of carbon emissions by greater São Paulo in 2003 (COPPE 2005) and approximately two years of carbon emissions by greater São Paulo today.

CONSERV1 had the least deforestation by 2030, with an emission of 46.0 × 10^6 Mg of carbon. CONSERV2 emitted 67.2 × 10^6 Mg of carbon, or 19.1% more than BAU1 (without BR-319) in 2030. BAU2 emitted 80.3 × 10^6 Mg of carbon.

Other Sources of Emission

Our paper only models deforestation, plus loss of small areas of non-forest vegetation present in the area, and associated net emission from biomass loss. Including other emission sources would increase total impact attributed to opening Highway BR-319 and augment benefits of creating protected areas, but would not alter our overall results. Soil carbon release in cleared areas would increase emissions in direct proportion to deforestation. Converting Amazonian forest to cattle pasture under normal management releases an average of 7.5 MgC ha^{-1} from the top 20 cm of soil, plus 5.6 MgC ha^{-1} from the 20-100-cm layer and 0.6 MgC ha^{-1} from the 1-8 m layer (Fearnside and Barbosa 1998). Carbon release from deeper layers only occurs over a long time.

This paper only considers carbon emissions (i.e., carbon as CO_2). Deforestation not only emits carbon as CO_2 but also trace gases such as CH_4 and N_2O. Compared to carbon emissions without considering trace gases, including trace gases would increase global warming impact of net committed emissions from deforestation by 11.5% for a 100-year time period and 26.3% for a 20-year period (more relevant for avoiding a “dangerous” 2°C temperature increase). These percentages (updated from Fearnside 2000) consider median emission factors for combustion from Andreae and Merlet (2001) and global warming potentials (with feedbacks) from the Intergovernmental Panel on Climate Change fifth assessment report (Myhre et al. 2013, p. 714).

In addition to deforestation, forest degradation through logging also releases carbon. Since much logging is illegal, it typically takes place without “reduced impact” precautions. Emissions from such conventional logging are substantial since many trees are killed in addition to those actually harvested. For example, committed emission from biomass loss in conventional logging at a typical harvest intensity of 38 m^3 ha^{-1} in Paragominas, Pará was 30.9 MgC ha^{-1}, or 14.5% of the carbon stock (above- and below-ground) in live and dead biomass (Veríssimo et al. 1992; see Fearnside 1995, p. 316).

Fire also degrades forest and releases carbon. Logging substantially increases vulnerability of forest to fire (e.g., Alencar et al. 2006), as do continued increases of deforestation and pasture that provide initial ignition sources for forest fires. When fires occur, the magnitude of committed emissions is highly variable: percentages of above- ground live biomass released (including decomposition of trees killed by fire) have been estimated for different fires at 63% (Cochrane and Schulze 1999), 51% (Barlow et al. 2003), and 14.4% (Vasconcelos et al. 2013).

All additional emission sources add to impacts of deforestation processes exacerbated by rebuilding BR-319. Conversely, they also add to the benefit of avoiding the construction of this road.

Conclusions

Reconstructing Highway BR-319 would increase deforestation in the southern portion of Brazil’s Roraima state, a location far removed from Highway BR-319 itself. Given our model assumptions, we estimate that deforestation would increase between 18 and 42% by 2030. Simulated carbon emissions would increase by a similar percentage, between 19 and 42%.

Under "business-as-usual" model conditions (BAU2), opening BR-319 implies an increase in emissions over a 23-year simulation totaling 23.9 million Mg (tons) of carbon. For comparison, this represents approximately two years of carbon emission by greater São Paulo today.

Our study showed that reconstructing BR-319, linking Manaus to Porto Velho, may have environmental impacts well beyond its official area of influence. Its effects can radiate to southern Roraima, which is already accessible by existing roads from the BR-319 roadhead in Manaus. These impacts should be considered in decision making on the BR-319 recuperation project. Mitigation measures that would reduce these impacts include creating conservation units in Roraima for areas most vulnerable to deforestation if BR-319 is rebuilt.

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Figure legends

Fig. 1. (A) Brazil with regions and states. (B) Brazil with locations mentioned in text. (C) Roraima state.

Fig. 2. (A) Brazilian Legal Amazonia (B) Southern Roraima; E.S. = Ecological station; I.L.= Indigenous Land; N.F. = National Forest and; N.P. = National Park. BR indicates federal highways; Municipal seats: 1 = Caracaraí, 2 = Rorainopolis, 3 = São Luiz do Araua, 4 = São João da Baliza, 5 = Caroebe.

Fig. 3. Conceptual diagram of the AGROECO model (adapted from Vitel 2009). The model's non-spatial portion is in Vensim software, and the spatial portion is in DINAMICA-EGO software. Static variables include soil type, vegetation, altitude and topography. Dynamic variables include distance to previous deforestation, distance to roads, and status as a settlement or as a protected area. (t=tn) = Map at time "t" (iteration) of the simulation; (P(rd)) = Probability for regrowth → deforested (clearing); (P(dr)) = Probability of deforested → regrowth and; (P(fd)) = Probability of forest →deforested.

Fig. 4. Land-use and cover maps of the study area for 2004 (A) and 2007 (B) used as the initial map and for calculating 2004-2007 transition rates. In our study area, "non-forest" refers to *campina*, a woody scrub vegetation on oligotrophic soils (low-nutrient white-sand soils) in seasonally flooded areas along the Branco River.

Fig. 5. Examples of weights of evidence of some dynamic variables used in our model: distance to secondary roads (A), distance to deforestation (B), distance to main roads (C) and distance to rivers (D). Higher values of weights of evidence (W^+) result in higher probability that the corresponding transition (such as

deforestation) will take place.

Fig. 6. Conservation Units (CUs) proposed in the conservation scenarios.

Fig. 7. Increased detail comparing simulated and observed deforestation in 2007 (B) in the southern portion of Brazil's state of Roraima (Brazil, INPE, 2008) for validation of the model. The historical landscape (A) represents deforestation detected by the PRODES program on LANDSAT-TM imagery for 2007. Simulated deforestation starts from PRODES deforestation present in 2004 and adds simulated clearing up to 2007 based on the model specifications.

Fig. 8. Cumulative deforestation under four simulated scenarios from 2007 to 2030 for the southern portion of Brazil's Roraima state.

Fig. 9. Scenarios for deforestation simulated from 2007 to 2030 in southern Roraima: (A) baseline scenario (BAU1), (B) BAU2 scenario, (C) conservation scenario 1 (CONSERV1) and conservation scenario 2 (CONSERV2). In the two BAU scenarios roads planned for the future are indicated by year of implementation in the model. In conservation scenarios, three proposed conservation units are shown. In our study area "non-forest" refers to *campina*, a woody scrub vegetation on oligotrophic soils (low- nutrient white-sand soils) in seasonally flooded areas along the Branco River

Fig. 10. Map of elevation and of the locations of settlement projects, indigenous lands and conservation units. Land invasions were observed adjacent to settlement projects and indigenous lands.

Table 1. Schedule for construction and paving of planned roads in the AGROECO model [a]

Year	Road name	Length (km)	Area (ha)[b]	Municipality
2008	BR-174 and BR-210	526	–	All
2009	BR-210 segment	63	75,600	São João/Caroebe
2011	Secondary roads	140	168,000	Rorainópolis
2012	RR-170 and BR-422	136	163,200	Caracaraí/Rorainópolis
2013	Roads in the Engano River region	264	316,800	Caracaraí
2014	Roads in the Jatapú Dam region	73	87,600	Caroebe
2015	Continuation of the Vincinal 07 road	65	78,000	Caroebe
2018	Road to Sta. Maria do Boiuçú	126	151,200	Rorainópolis
Total	–	**867**	**1,040,400**	–

[a]For all scenarios except some destinations in the conservation scenarios.

[b]Available area for deforestation

Table 2. Premises for the scenarios.

Scenario	**BR-319 Highway**	**Planned local roads**	**Conservation units**	**Migration factor**
BAU1	No	Yes	No	No
CONSERV1	No	No	Yes	No
BAU2	Yes	Yes	No	Yes
CONSERV2	Yes	No	Yes	Yes

Table 3. Average biomass (below- and above-ground) present in forests in Roraima state in 2007.

Code[a]	Forest type	Value	Pixels by forest type[b]	Biomass (above + below ground)	Inventories	Forest biomass stock	Forest carbon stock
		No.	No.	Mg ha^{-1}	No.	Mg	Mg
LO	Contact zone: rainforest & vegetation on white sand	**15**	149,864	384.6	274	360,264,646	174,728,353
Fs	Seasonal semideciduous forest, submontane	**10**	187	315.7	33	368,951	178,941
Ab	Open-canopy rainforest on non-flooding lowlands	**6**	36,318	363.4	265	82,494,236	40,009,705
As	Open-canopy rainforest, submontane	**7**	87,053	336.0	618	182,824,258	88,669,765
Da	Dense-canopy rainforest on river floodplain	**14**	38,542	360.8	144	86,918,604	42,155,523
Db	Dense-canopy rainforest on non-flooding lowlands	**13**	229,923	384.5	517	552,537,610	267,980,741
Dm	Dense-canopy rainforest, montane	**11**	20,845	361.3	27	47,070,899	22,829,386
Ds	Dense-canopy rainforest, submontane	**12**	415,241	385.3	533	1,000,042,511	485,020,618
La	Open Woody Oligotrophic Vegetation of	**8**	26,939	60.6	[c]	10,206,025	4,949,922

	swampy & Sandy areas						
Ld	Dense Woody Oligotrophic Vegetation of swampy & Sandy areas	**4**	100,589	365.0	[d]	229,468,656	111,292,298
Lg	Grassy-woody Oligotrophic Vegetation of Swampy & Sandy areas	**3**	7,727	46.0	[e]	2,221,513	1,077,434
Sa	Open Woodland Savanna	**2**	13,506	44.7	[f]	3,772,825	1,829,820
Sg	Grassland Savanna	**1**	524	12.6	[f]	41,177	19,971
	Total	–	**1,127,258**	–	–	**258,231,911**	**1,240,742,477**

[a] Brazil, IBGE (2012).

[b] Pixel resolution: 250 m (6.25 ha).

[c] Barbosa and Ferreira (2004) and 2.81 (root/shoot) for root fraction (R.I. Barbosa Pers. comm.; see Barbosa et al. 2012).

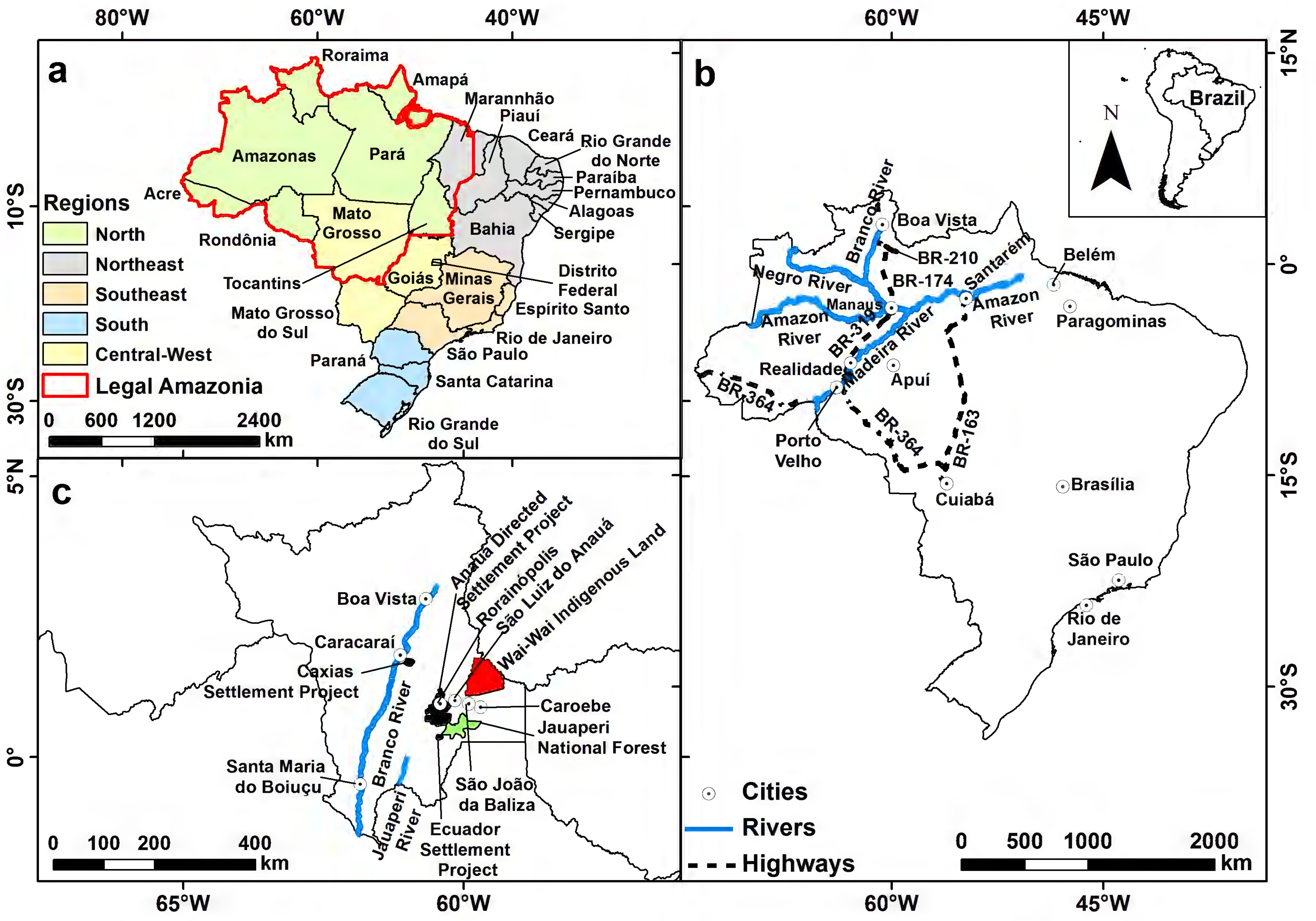
[d] Estimates from Brazil, Projeto RADAMBRASIL (1973-1983).

[e] Estimates from Kauffman et al. (1988) and Klinge et al. (1975).

[f] Barbosa and Fearnside (2005) and 2.81 (root/shoot) for root fraction (R.I. Barbosa Pers. comm.; see Barbosa et al. 2012).

Table 4. Estimates of forest biomass and carbon emissions in 2030

Scenario	**Cumulative deforested area**	**Growth 2007/2030**		**Forest biomass**	**Forest carbon**	**Carbon absorbed by replacement vegetation**	**Net carbon emission**
	hectares	**hectares**	**%**	**Mg**	**Mg**	**Mg**	**Mg**
BAU1	715,250	342,612	91.9	126.7×10^6	61.5×10^6	5.1×10^6	56.4×10^6
CONSERV1	654,513	281,876	75.6	104.1×10^6	50.5×10^6	4.5×10^6	46.0×10^6
BAU2	858,639	486,001	130.4	178.2×10^6	86.4×10^6	6.1×10^6	80.3×10^6
CONSERV2	775,888	403,250	108.2	149.7×10^6	72.6×10^6	5.4×10^6	67.2×10^6


80°W
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40°W
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a
Roraima
Amapá
Marannhão
Piauí
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Rio Grande do Norte
Paraíba
Pernambuco
Alagoas
Sergipe
Bahia
Amazonas
Pará
Acre
Rondônia
Mato Grosso
Tocantins
Goiás
Minas Gerais
Distrito Federal
Espírito Santo
Mato Grosso do Sul
Rio de Janeiro
São Paulo
Paraná
Santa Catarina
Rio Grande do Sul
Regions
North
Northeast
Southeast
South
Central-West
Legal Amazonia
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b
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Branco River
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São Luiz do Anauá
Wai-Wai Indigenous Land
Boa Vista
Caracaraí
Caxias Settlement Project
Branco River
Caroebe
Jauaperi National Forest
Santa Maria do Boiuçu
São João da Baliza
Jauaperi River
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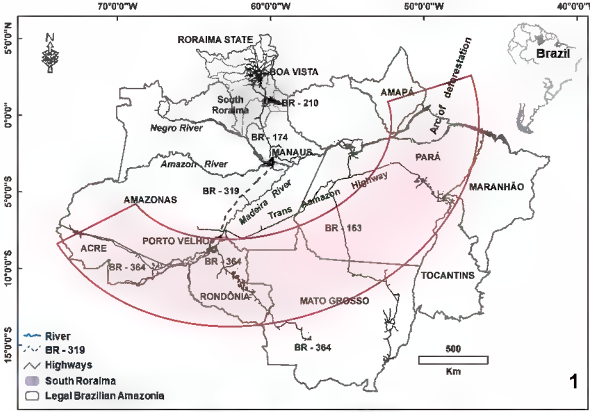
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N
RORAIMA STATE
BOA VISTA
South Roraima
BR - 210
BR - 174
Negro River
MANAUS
Amazon River
AMAPÁ
Arc of deforestation
Brazil
PARÁ
MARANHÃO
AMAZONAS
BR - 319
Madeira River
Trans Amazon Highway
BR - 163
PORTO VELHO
ACRE
BR - 364
BR - 364
RONDÔNIA
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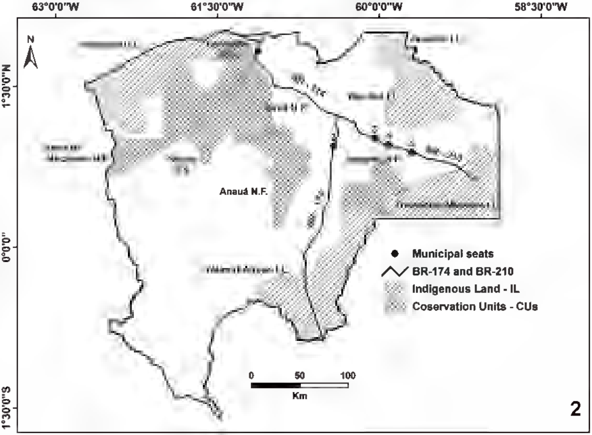
Legal Brazilian Amazonia
1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Municipal seats
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Indigenous Land - IL
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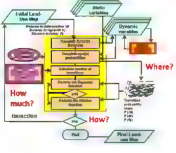
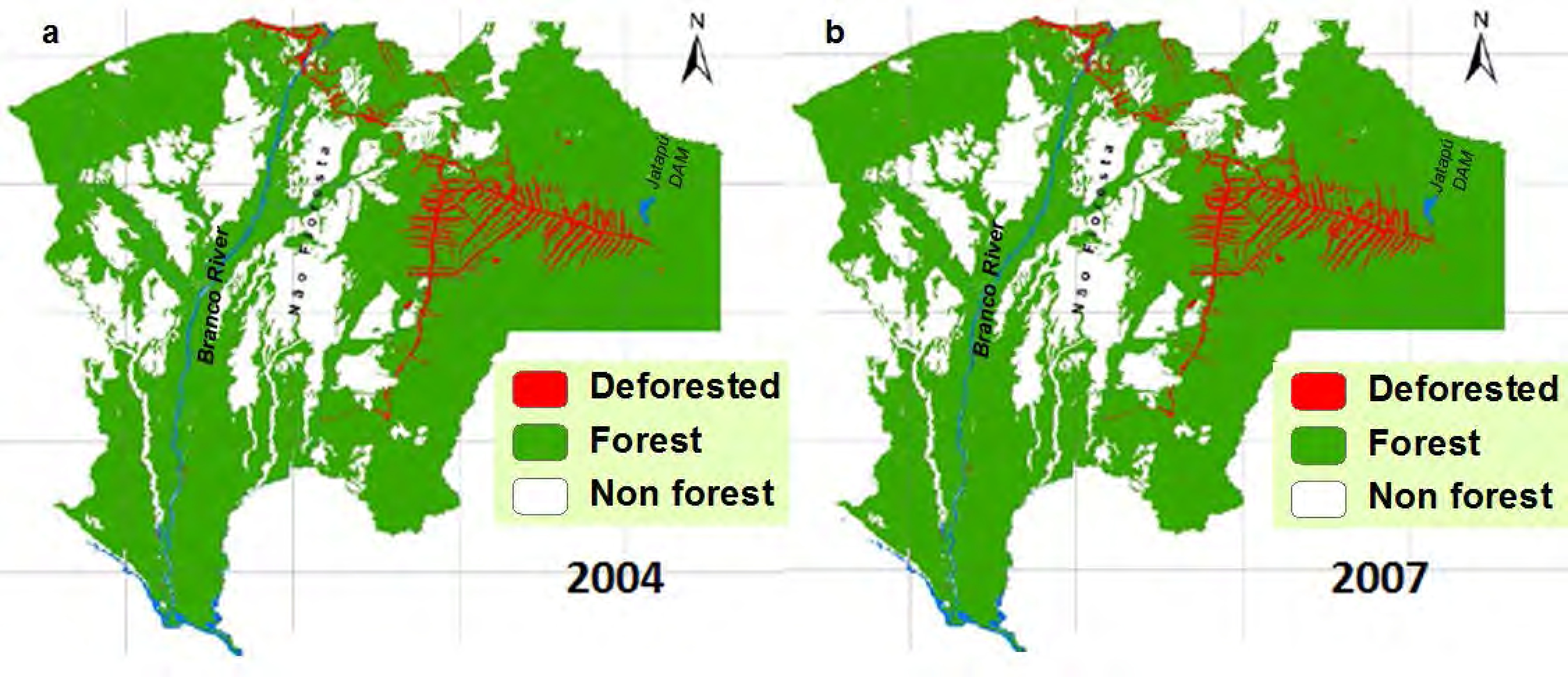
2

The AGROECO model




a
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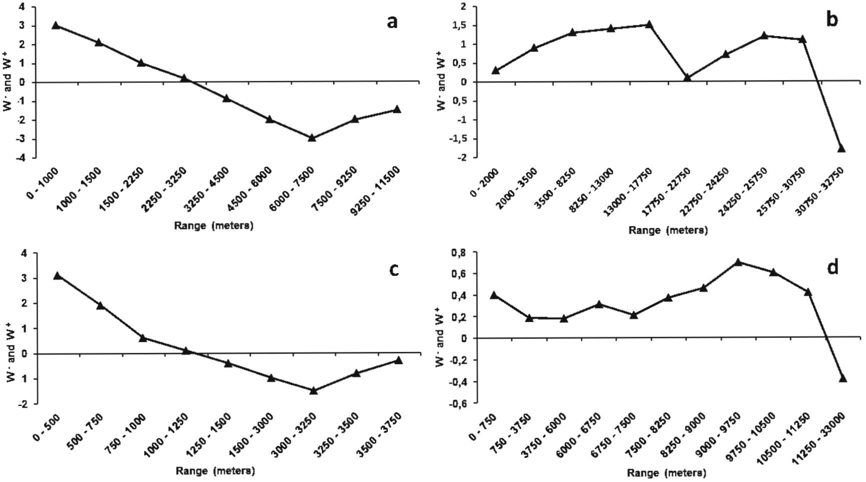
Jatapú DAM
Branco River
Não Floresta
Deforested
Forest
Non forest
2004
b
N
Jatapú DAM
Branco River
Não Floresta
Deforested
Forest
Non forest
2007


a
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W⁻ and W⁺
Range (meters)
0 - 1000
1000 - 1500
1500 - 2250
2250 - 3250
3250 - 4500
4500 - 6000
6000 - 7500
7500 - 9250
9250 - 11500
0 - 2000
2000 - 3500
3500 - 8250
8250 - 13000
13000 - 17750
17750 - 22750
22750 - 24250
24250 - 25750
25750 - 30750
30750 - 32750
0 - 500
500 - 750
750 - 1000
1000 - 1250
1250 - 1500
1500 - 3000
3000 - 3250
3250 - 3500
3500 - 3750
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750 - 3750
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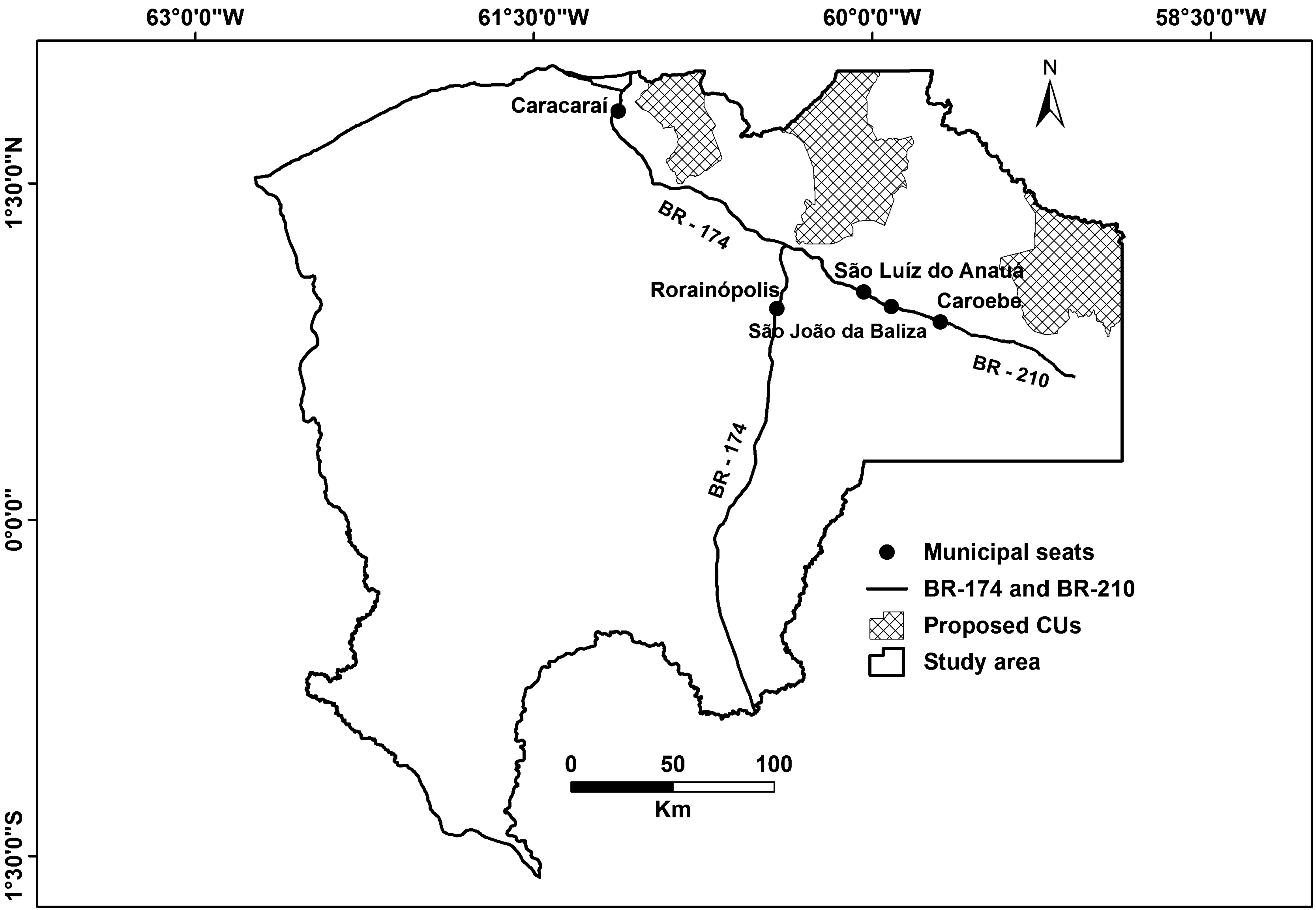
10500 - 11250
11250 - 33000


63°0'0"W
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Caracaraí
BR - 174
São Luíz do Anauá
Rorainópolis
Caroebe
São João da Baliza
BR - 210
BR - 174
Municipal seats
BR-174 and BR-210
Proposed CUs
Study area
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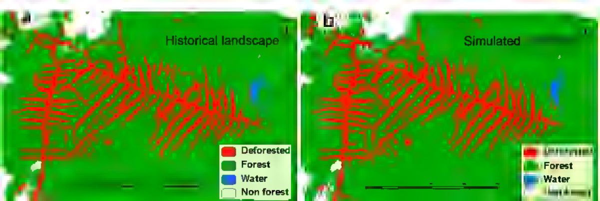
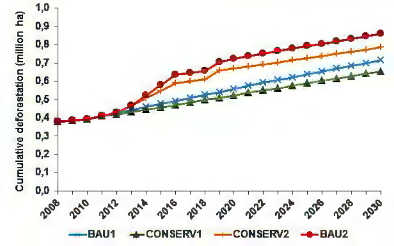
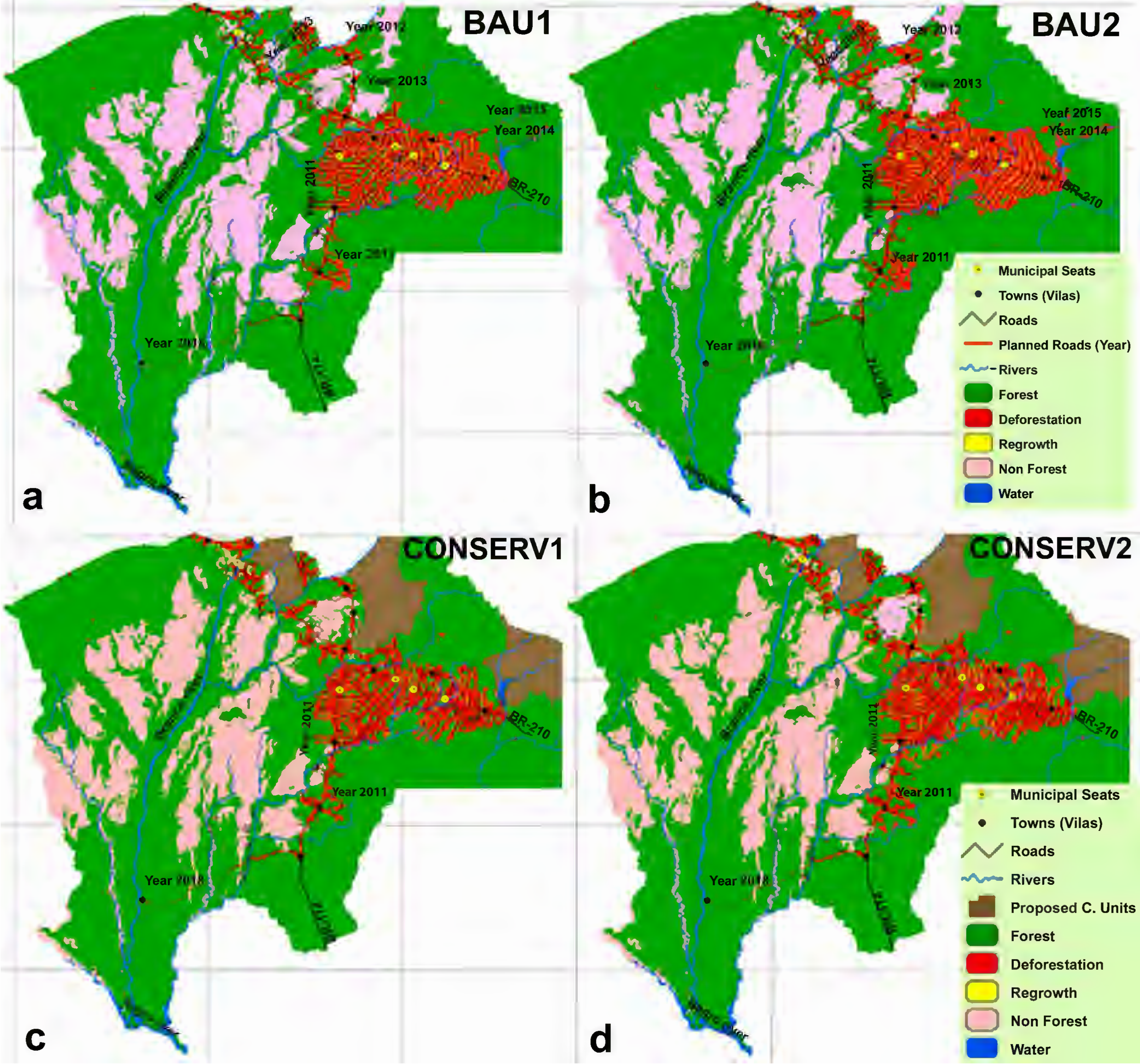
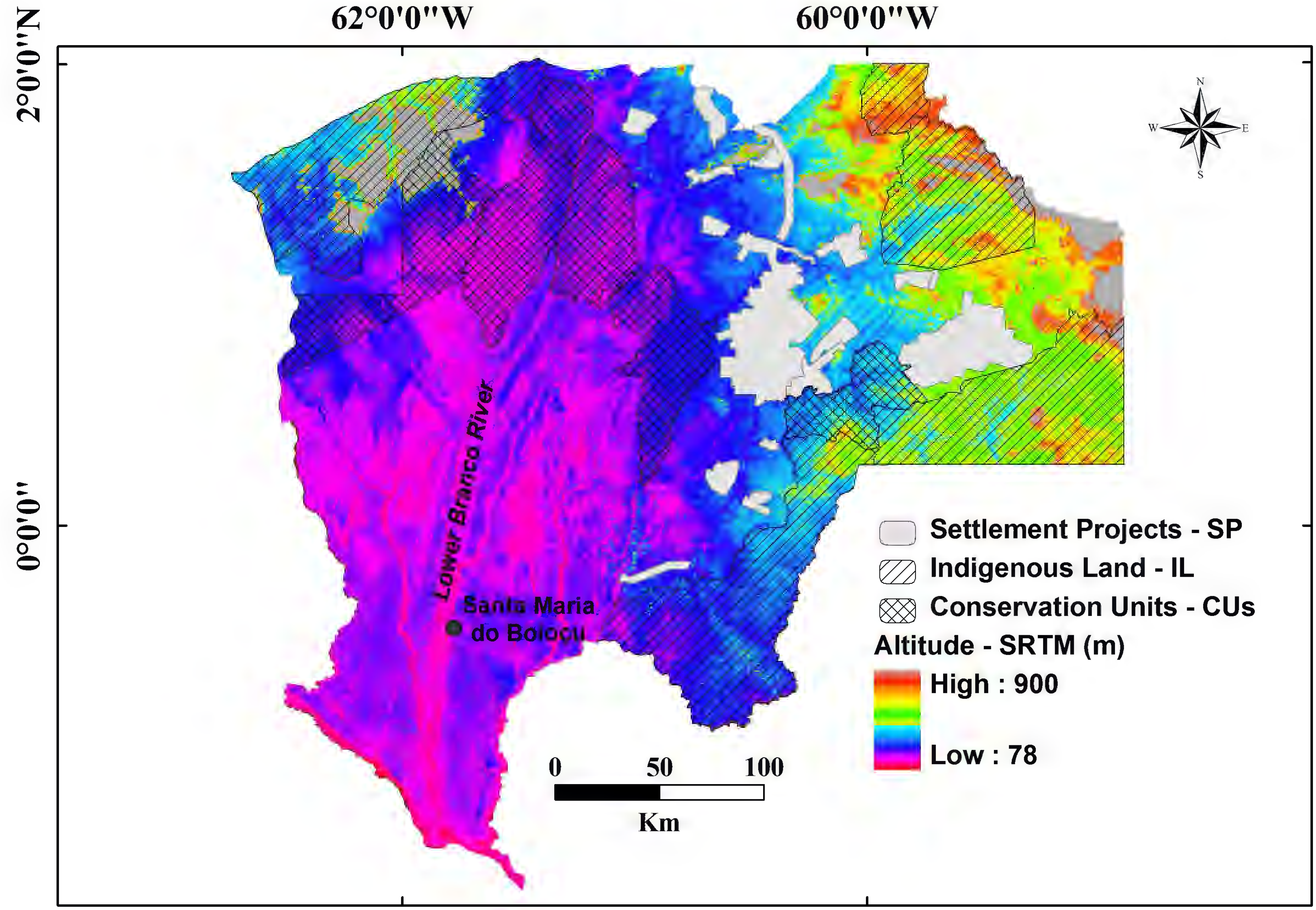

a
Historical landscape
Deforested
Forest
Water
Non forest
b
Simulated
Forest
Water



Cumulative deforestation (million ha)
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
2008
2010
2012
2014
2016
2018
2020
2022
2024
2026
2028
2030
BAU1
CONSERV1
CONSERV2
BAU2


BAU1
Year 2012
Year 2013
Year 2015
Year 2014
Year 2011
BR-210
Year 2011
a
BAU2
Year 2012
Year 2013
Year 2015
Year 2014
Year 2011
BR-210
Year 2011
b
Municipal Seats
Towns (Vilas)
Roads
Planned Roads (Year)
Rivers
Forest
Deforestation
Regrowth
Non Forest
Water
CONSERV1
Year 2011
BR-210
Year 2011
Year 2018
c
CONSERV2
Year 2011
BR-210
Year 2011
Year 2018
d
Municipal Seats
Towns (Vilas)
Roads
Rivers
Proposed C. Units
Forest
Deforestation
Regrowth
Non Forest
Water



62°0'0"W
60°0'0"W
2°0'0"N
0°0'0"
Lower Branco River
Santa Maria do Boiaçu
N
S
E
W
0
50
100
Km
Settlement Projects - SP
Indigenous Land - IL
Conservation Units - CUs
Altitude - SRTM (m)
High : 900
Low : 78

Supplementary Online Material

Simulating deforestation and carbon loss in Amazonia: impacts in Brazil's Roraima state from reconstructing Highway BR-319 (Manaus-Porto Velho)

1. Road-Building Module

DINAMICA-EGO software's road-building module is directed by a set of maps that either favor or restrict advancement of roads. In the AGROECO model (Fig. S1), this module also creates an area of "accessible forest," which is a 2-km strip on each side of both planned roads and endogenous roads (created automatically). This area of forest is highly favorable for deforestation, as it simulates occupation area of land plots (e.g. Fearnside et al. 2009; Yanai et al. 2012).

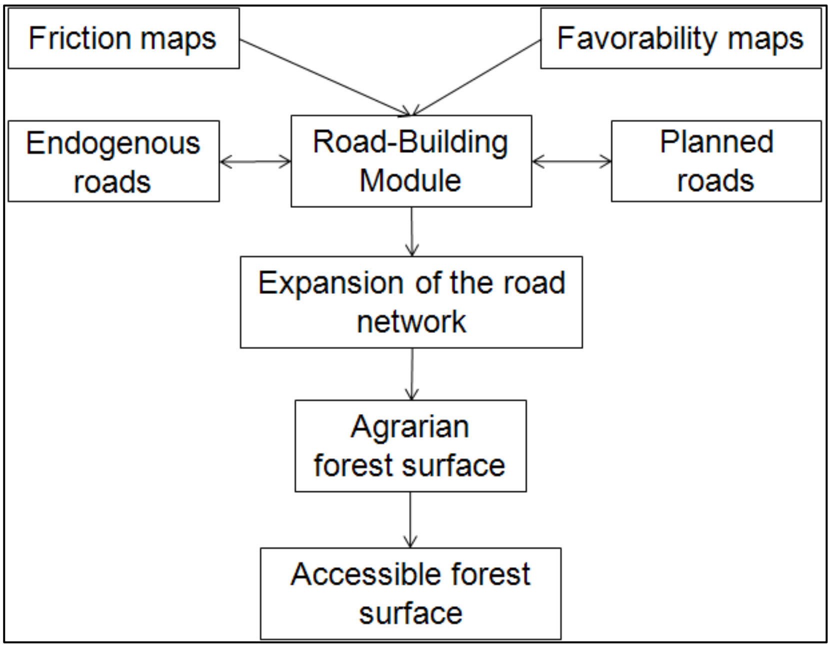


Fig. S1. Illustration of data flow in the AGROECO model for delimitation of the "accessible forest" area.

2. Calculation of Weights of Evidence

Weights of evidence originate from the Bayesian method of conditional probability. In modeling dynamics of land-use and land-cover change, they are applied to calculate *a posteriori* probabilities of a pixel being deforested, given *a priori* knowledge of favorable local conditions for deforestation. In this step of modeling maps of land use, the static and dynamic variables were combined in a DINAMICA-EGO sub-template for extracting weights of evidence (Soares-Filho et al. 2014).

The influence of weights of evidence on the variables can be positive (favoring deforestation) or negative (inhibiting deforestation). The weights of evidence are recalculated at each iteration of the model considering the total area of forest available in a given iteration.

In the simulation the weights of evidence represent the "amount" of influence of each variable on the spatial transition probability of a cell in a particular state (i) changing to another state (j) depending on its location within a given range of distance. Thus, the most likely state change will occur in the cell whose location is closest to the range of the classes of interest. This relationship is given by Equations (1) to (9):

$$P(D|A) = \frac{P(D \cap A)}{P(A)} \quad (1)$$

$$P(A|D) = \frac{P(A \cap D)}{P(D)} \quad (2)$$

$$P(A \cap D) = P(A|D) \times P(D) \quad (3)$$

In the same fashion, considering the non-event D, as non-D ($\bar{D}$), one obtains: (4)

$$P(\bar{D}|A) = P(\bar{D}) \times \frac{P(A|\bar{D})}{P(A)} \quad (4)$$

Substituting (4) in (1), one obtains (5):

$$P(D|A) = P(D) \times \frac{P(A|D)}{P(A)} \quad (5)$$

Applying the ratio between Equations (6) and (7), one obtains (8):

$$O(D|A) = O(D) \times \frac{P(A|D)}{P(A|\bar{D})} \quad (6)$$

(7)

$$log\ O(D|A) = log\ O(D) + log \frac{P(A|D)}{P(A|\bar{D})}$$

$$log\ O(D|A) = log\ O(D) + W^{+} \quad (8)$$

Therefore:

$$log\ O(D|A_i) = log\ O(D) + \sum_{i=1}^{n} W_i^{+} \quad (9)$$

Where “{D}” and “O {D/A}” are ratios of *a priori* probabilities of event “D” occurring, and of event “D” occurring given a spatial pattern “A,” respectively. “W^{+}” is, therefore, the weight of evidence of the event D occurring given a spatial pattern “A.” *A posteriori* spatial probability of a transition “i → j” from a set of spatial data “(B, C, D, ... N)” is expressed as: (10)

$$P(i \rightarrow j|B \cap C \cap D \dots \cap N) = \frac{e^{\sum W_i^+}}{1 + e^{\sum W_i^+}} \quad (10)$$

Where, "B, C, D, ..., N" are values of k spatial variables measured at position "x, y" and are represented by their weights "W^+ N."

3 . The Patcher and Expander Functions

DINAMICA-EGO uses a local rule for the cellular automaton algorithm, where is a transition mechanism composed of two complementary functions: Patcher and Expander (Fig. S2). The Patcher function searches for cells around a location that has been chosen (through a seeding mechanism) for a combined transition for formation of a new deforestation patch. This is done by first choosing the central cell of a new patch and then selecting a specific number of cells surrounding the central cell based on a transition probability "P (i → j)" calculated from the weight of evidence. The Expander function is only dedicated to expansion or contraction of previous patches of a given class. In the Expander function, a new spatial transition probability "P (i → j)" depends on the number of cells of type j around a cell of type i. For constructing the scenarios, the transitions used were "forest → deforestation" (1 → 3), "deforestation → regeneration" (1 → 2) and "regeneration → deforestation" (2 → 1).

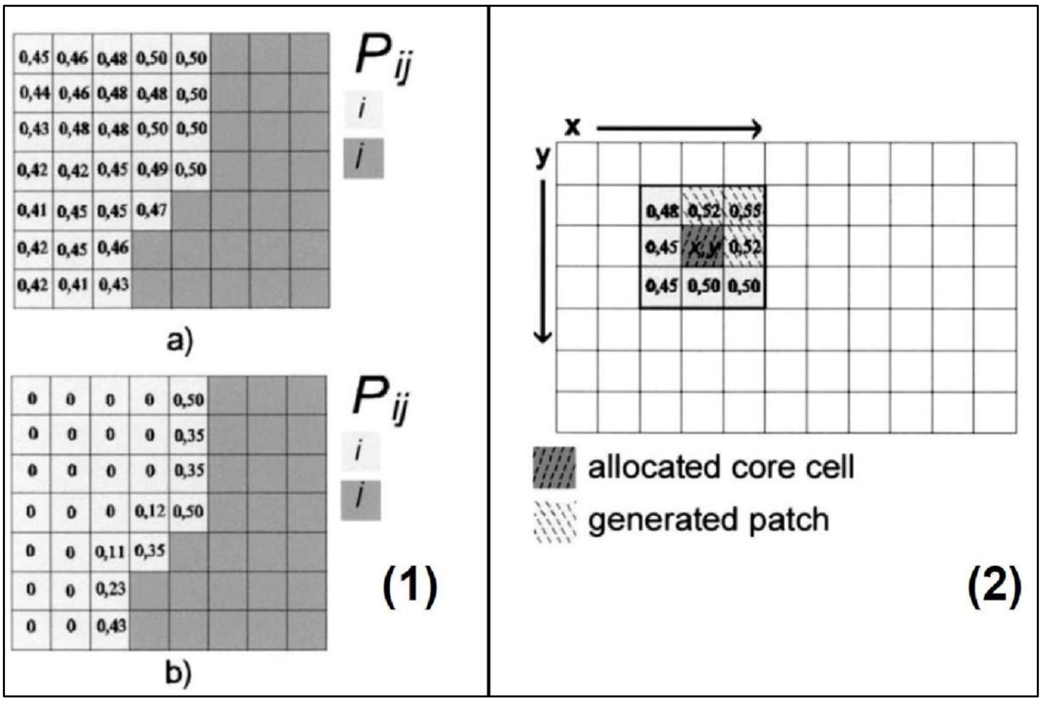


Fig. S2. *Pij* arrays before (a) and after (b) applying the Expander function (1) and the selection of cells around a core cell allocated by the Patcher function (2). Adapted from Soares-Filho et al. (2002).

Parameters used for the Patcher and Expander functions in the four simulated scenarios were the same for the transition "forest → deforestation" (3 → 1). Means and variances of deforestation polygons were derived for the study area (Barni et al. 2012) and were 12.5 ha, 62.5 ha and 1.7 for the mean, variance and isometry values, respectively. The partition between the two change functions was 75% for Patcher and 25% for Expander.

Equal values were also used for the transitions "deforestation → regeneration" (1→2) and "regeneration → deforestation" (2→1). The parameters were 6.5 ha (one pixel) and 0 (zero) for the mean and variance, respectively, for the polygons with these transitions, with an isometry value of 1.7. The partition between the two change functions was 65% for Patcher and 35% for Expander for both transitions.

4. Available forest

New deforestation expansion fronts have been detected linked with logging activities (Barni et al. 2012). In three of these fronts we suggest creating conservation units as part of the modeling exercise. Approximately 40% of these forests are accessible due to proximity to roads; these areas are distributed between existing projects and indigenous lands (Table S1). However, some blocks of continuous forest are accessible only by river transport on the Branco River (e.g., in Santa Maria do Boioçu).

Table S1. Areas of use classes in southern Roraima.

Use class description	Area (km^2)	Percentage
Southern portion of Roraima	98,955.1	44.1% of the state
Forest	84,910.6	85.8% of southern Roraima
Non forest	14,044.5	14.2% of southern Roraima
Indigenous Land (I.L.)	22,737.8	23.0% of southern Roraima
Conservation Units (C.U.)	13,849.2	14.0% of southern Roraima
Settlements	6,038.7	6.1% of southern Roraima
Deforestation*	3,689.6	3.7% of southern Roraima
Deforestation in settlements	2,420.3	65.6% of area in settlements
Regrowth and degraded pastureland	2,767.2	75.0% of southern Roraima (from Terra class)
Available forest**	41,015.6	41.4% of southern Roraima

* Deforestation up to 2010 in southern Roraima (Brazil, INPE 2014)
** Remaining forest without any protection status and outside of settlement projects.

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