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Avoided Deforestation in Brazilian Amazonia: Simulating the effect of the Juma Sustainable Development Reserve

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ABSTRACT

The Juma Sustainable Development Reserve, located in Brazil's state of Amazonas, was the first protected area in Brazil to be benefited by a Reducing Emissions from a Deforestation and Degradation (REDD) project. However, the carbon benefits of REDD projects may be compromised by leakage, or displacement of deforestation to areas outside of the reserve. Through environmental modeling techniques it is possible to simulate scenarios that represent changes in land use and land cover and thus assess the possible trajectories and magnitude of deforestation. The aim of this study was to evaluate the effectiveness of the Juma reserve in reducing deforestation and to estimate projected carbon emission by 2050. The simulated scenarios were: 1) baseline scenario, without the creation of the Juma reserve; 2) scenario with leakage (SL) where the creation of the reserve would cause a spatial shift in deforestation, and 3) scenario with reduced leakage (SRL), where the amount of deforestation resulting from leakage is reduced. Considering the study area as a whole (Juma reserve + 120-km buffer zone), there would be a 16.0% (14,695 km^2) reduction in forest cover by 2050 in the baseline scenario, 15.9% (14,647 km^2) in the SL and 15.4% (14,219 km^2) in the SRL, as compared to what was present in 2008. The loss of forest cover within the limits of the Juma reserve by 2050 would be 18.9% (1,052 km^2) in the baseline scenario and 7.1% (395 km^2) in the SL and SRL. From the simulated scenarios, the carbon stock in the total study area was estimated to be reduced from 1.63 Pg C (Pg = 10^{15} g = 1 billion tons) in 2008 to 1.37 Pg C in 2050 in the baseline scenario and in the SL and to 1.38 Pg C in the SRL. In the area of the Juma reserve, the carbon stock would be reduced from 0.10 Pg C in 2008 to 0.08 Pg C in 2050 (baseline) or 0.09 Pg C (SL and SRL). The Juma reserve was effective in reducing carbon emission by 2050, but the reduction would be substantially less than that calculated in the Juma REDD project. Leakage must be accounted for in REDD projects because the deforestation resulting from this effect could generate "hot air" (carbon credit with no additionality). Over longer time horizons the benefits of reserves are greater and leakage losses are recovered.

Keywords: REDD, land cover change, modeling, leakage, protected areas, carbon emissions

1. Introduction

The global emissions of greenhouse gases associated with burning fossil fuels and changes in land use have already reached 9 Pg C year^{-1} (IPCC, 2007) (1 Pg = 10^{15} g = 1 billion tons). Emissions from land-use change represent 10-12% (van der Wert et al., 2009) to 17% (IPCC, 2007) of global anthropogenic emissions. In Brazil, 77% (0.34 Pg C) of the carbon emissions in 2005 are attributed to land use, land-use change and forestry (MCT, 2010).

In Brazilian Amazonia, deforestation has historically been concentrated in the "arc of deforestation" along the southern and eastern edges of the forest, but recently it has advanced to the southern part of the state of Amazonas (Becker, 2005; INPE, 2010). In response, one of the strategies implemented to contain the deforestation in this region is creation of protected areas. These areas, in addition to impeding deforestation (Ferreira et al., 2005; Nepstad et al., 2006), play a basic role in providing environmental services such as biodiversity maintenance, water cycling and carbon storage (Fearnside, 2008a; Wunder et al., 2008).

Creation and management of protected areas in Amazonia is costly (IDESAM, 2009). For this reason, financial mechanisms have been promoted to obtain resources for conservation of the tropical forests, such as Reduction of Emissions from Deforestation and Degradation (REDD) projects (Nepstad et al., 2007; Stickler et al., 2009). REDD mechanisms are the subject of considerable controversy concerning their effectiveness, their social and economic impacts and their proper place in global-warming mitigation (see reviews by Angelson, 2008; Moutinho et al., 2011; Fearnside, 2011, 2012). Brazilian federal and state governments consider REDD to be an important instrument for combating deforestation and valuing tropical forests for one of their environmental services, thereby mitigating climatic change (SDS, 2008). The REDD project in the Juma reserve was developed and validated in 2008 and is the first avoided deforestation project in Brazil. Carbon stored in the forests that are threatened by deforestation and degradation is rewarded through payment to the local communities to conserve the forest (Ghazoul et al., 2010). The approach used by the Juma REDD project to justify its carbon benefits was based on a baseline projected through the use of models. "Additionality," or the reduction of emissions as compared to what would have occurred without the project, is established by comparing monitored results with a hypothetical baseline representing the projection of deforestation and greenhouse-gas emissions in a no-project scenario. Depending on the approach and the assumptions considered in the simulation model, modeled baselines can be either higher or lower than baselines that simply extrapolate historical deforestation (Fearnside, 2011; Parker et al., 2009). There is concern that REDD projects could only displace deforestation to locations outside the limits of the project, that is, they result in "leakage" (Wunder et al., 2008). This includes "in-to-out" leakage (where the actors move to areas outside of the reserve) as well as "out-to-out" leakage (where new actors migrating to the region to establish clearings in forest areas are diverted, instead, to sites of outside of the reserve) (Fearnside, 2009). It is important that this effect be measured to evaluate the level of susceptibility of the project and to assure the additionality and permanence of the project are real. The credibility and viability of a REDD project can be seriously compromised by factors such as a poorly dimensioned baseline for the projection of deforestation and the absence of accounting for the effect of leakage.

Deforestation rates in Brazilian Amazonia have varied substantially over time and among locations in the region (e.g., Fearnside, 2005, 2008a). Between 2004 and 2011 the overall deforestation rate declined by about half. The greatest declines were in areas of "consolidated" agriculture and ranching, such as the state of Mato Grosso, while declines were smaller in "frontier" areas such as most of the area of the current study. The overall decline in deforestation from 2004 to 2008 was closely associated with the international prices of export commodities such as soybeans and beef, and with the exchange rate between the Brazilian real and other currencies – the value of the real doubled relative to the US dollar between 2002 and 2007 and maintained values above this level through mid-2012, making export of Amazonian commodities less profitable and discouraging clearing. After 2008 the economy began to recover but deforestation rates continued to decline, presumably reflecting increased control efforts (Hargrave and Kis-Katos, 2011; Assunção et al., 2012). Expenditure on enforcement correlates with decline in deforestation by municipality over this period (Barreto et al., 2011).

The present study was carried out with the intention of (1) evaluating the effect on deforestation of creating the Juma reserve and (2) estimating the carbon emissions in simulated scenarios with and without the reserve over the 42-year period from 2008 to 2050. Three scenarios were simulated using the framework of the AGROECO model developed by Fearnside et al. (2009a): The Baseline Scenario represents what would happen in the coming years if the Juma reserve had not been created; the Scenario with Leakage (SL) considers the creation of the Juma reserve and the effect of leakage due to its presence; the Scenario with Reduced Leakage (SRL) considers the creation of the reserve and a reduction of the effect of the projected leakage due to the presence of the reserve.

The intention of this study is to contribute to improving the current methodology used in REDD projects in the state of Amazonas and to evaluate the effect of protected areas in reducing deforestation in areas under anthropogenic pressure.

2. Methods

2.1. Study area

The Juma reserve was created by Decree n^{o}. 26,009 of July 2006 enclosing an area of 589,611 ha in the municipality (county) of Novo Aripuanã, in the southern portion of the state of Amazonas (SDS, 2010). This study considered the limits of the reserve and its surrounding area (a buffer of 120 km), totaling 9,742,625 ha (Fig. 1). The objective of the buffer was to include in the simulation the neighboring municipalities (Apuí and Manicoré) and the highways (AM-174 and stretches of BR-319 and BR-230) that influence the process of occupation in the region of the Juma reserve. This area also has other protected areas (seven indigenous lands, one integral-protection reserve and four sustainable-use reserves) and communities that live in and around the reserve, distributed along the edges of rivers and roads. These families make direct use of the natural resources of the reserve (SDS, 2010).

[Fig. 1 here]

The interior of the Juma reserve has well-conserved original forest cover; deforestation in the reserve is concentrated mainly along the AM-174 Highway, where illegal logging occurs together with family agriculture for the local communities (IDESAM, 2009). Other activities such as gold mining, cattle ranching and predatory fishing have contributed to the loss of natural resources in the reserve. The cumulative deforestation in the Juma reserve up to 2009 totaled 68.3 km^{2}, or 1.2% of the total area of the reserve (INPE, 2010).

2.2. Stages of the methodology

The methodology is divided into stages described in Fig. 2. The AGROECO spatial model of deforestation was used as a framework for constructing the scenarios (Fearnside et al., 2009a) (Fig. S1). This model was developed using DINAMICA EGO software (Rodrigues et al., 2007; Soares-Filho et al., 2009).

[Fig. 2 here]

Models developed in DINAMICA EGO are based on cellular automata, which consist of the following elements: cells (pixels), states, neighborhoods and transition rules (Jacob et al., 2008). The transition of a cell from one state to another is influenced by the state of the neighboring cells (Yeh and Li, 2006). All of the cells are updated simultaneously at each discrete time step (Sirakoulis et al., 2000).

The spatial resolution used was 250 m; therefore, the area of each cell is 6.25 ha. The cartographic projection applied was the UTM (Universal Transverse Mercator), corresponding to UTM Zone 20 South and Datum WGS 1984.

2.3. Elaboration of the input data

The input variables for the model consisted of land-cover maps, static variable map, attractiveness map, friction map, current and planned roads map (Table 1, Fig. S2) and the coefficients of the weights of evidence.

[Table 1 here]

2.3.1. Weights of evidence and calculation of the probability map

The “weights of evidence” statistical method determines the probabilities of a given event occurring based on one or more factors of evidence (Bonham-Carter et al., 1989). These probabilities are used in the model with the intention of determining the probability of a cell changing from a given state to another, given the evidence. The transitions considered were:

- **Deforestation**: Forest → Deforestation
- **Regeneration**: Deforestation → Secondary vegetation
- **Cutting of secondary vegetation**: Secondary vegetation → Deforestation.

The terms “deforestation” and “cutting of secondary vegetation” differ when referring to transition processes, but when referring to the value of a cell there is no distinction between the classes “deforestation” and “cutting secondary vegetation.” The factors considered as evidence in the study were the map of the static variables and maps of land cover and roads. Thus, for each iteration the model calculates and updates a map of transition probabilities. This map indicates the areas that are most favorable for each type of transition based on the Bayesian method of weights of evidence (Soares-Filho et al., 2002, 2009).

In the AGROECO model the secondary vegetation → forest transition was also considered. This transition is made automatically in the model through an accounting of permanence of the cells in secondary vegetation. Cells that remained uncleared for 30 iterations (years) were automatically transformed into forest. For this transition it was not necessary to use either weights of evidence or transition rates.

The assumption of the weights of evidence method is that the predictor patterns must to be conditionally independent (Bonham-Carter et al., 1989). DINAMICA EGO allows testing the independence assumption using a “functor” (subroutine) that determines weight of evidence correlation. This functor uses pairwise tests for categorical maps, such as the Cramer coefficient, the contingency coefficient and joint information uncertainty. Values of these indices below 0.5 are considered to represent adequate independence (Agterberg and Bonham-Carter, 2005). Thus, we tested the correlation between a pair of maps using a tutorial model available in DINAMICA EGO software (more information in supplementary online material).

2.4. Calculation of the transition rates

The transition rate represents the proportion of cells that will be transformed from one class to another, in accord with the previously established transitions. It is then necessary to multiply this rate by the number of cells in the given class in order to calculate the amount of change in terms of number of cells (gross rate). In this way, the rate of deforestation for the year "t" is multiplied by the extent of remaining forest for the year "t-1". With this, one obtains the area to be deforested in the year "t" expressed as the number of forest cells that will be transformed into deforestation.

AGROECO uses a concept of "agrarian forest surface" (AFS), which is modeled as a 2-km wide strip on each side of the roads. This stems from the term "agrarian area" (*área fundiária*) used to describe the perception of many small farmers settled along roadsides that they have a right to claim unoccupied land behind their properties. This perception has no legal basis, but it does influence behavior (Fearnside et al., 2009a). The areas (ha) of "AFS" and of "forest outside of the AFS" are updated in each iteration, in accord with the increment in roads and deforestation in the model.

2.4.1. Rate of deforestation

The deforestation rates (proportions) were calculated through the simultaneous transfer of data between DINAMICA EGO and Vensim. DINAMICA EGO passes a categorical map to Vensim with the following classes: forest, roads, deforestation, secondary vegetation and AFS. Vensim, in turn, calculates the deforestation rates using the equation in Table 2. This equation was developed using data on deforestation, forest and AFS from the maps for 2003 and 2008 (Table S1). First, the ratio was calculated between the average area deforested per year (2003 to 2008) and the area of forest in the AFS. A value of 0.02333 was obtained from this calculation. This value indicates that 2.33% of the forest in the AFS was deforested in this time interval. The calculation for the forest area outside of the AFS was done in the same way, yielding a value of 0.00023604. [Table 2 here]

2.4.2. Rate of regeneration and of cutting secondary vegetation

The rates used for regeneration and cutting secondary vegetation were constant (Table 2). This was necessary due to the lack of parameters and of data for elaborating a specific equation to be used in the calculation of these rates.

The rate of cutting secondary vegetation was estimated on the basis of the maps of land cover in 2003 and 2008. By overlaying these maps, the total area of cutting secondary vegetation was obtained for the five-year period. This value was later divided by the total area of secondary vegetation (2003), and the average area of cutting of secondary vegetation per year was calculated.

The rate of regeneration was estimated in a similar way. By overlaying the maps for 2003 and 2008 the average area regenerated per year was obtained for this five-year interval. This value was later divided by the average value of the deforested area that was present in the same time interval.

2.4.3. Rate of leakage of deforestation

In this study, leakage was due to the creation of the Juma reserve; thus, part of the deforestation that occurred inside of the reserve in the baseline scenario was distributed to other areas outside of its boundaries in the SL. The estimate of the leakage rate was obtained from the difference between baseline and the SL for 2050 in the area of the Juma reserve. This value was then divided by the total number of iterations in order estimate the number of cells displaced per year. Prior to this, the rates of deforestation without the effect of leakage had been calculated by means of equation of "rate without leakage" (Table 2).

"Cells of forest cut $(SL)_{year}$" is the total number of cells of forest deforested in a given year in the scenario with leakage, "Cells $leaked_{year}$" is the number of cells that were deforested inside the Juma reserve in the baseline that were displaced to outside the reserve in the scenario with leakage, and "Cells of forest $(SL)_{year}$" is the number of cells of remaining forest in a given year in the scenario with leakage. This value was added to the number of leaked cells to obtain an estimate of the total remaining forest without leakage in a given iteration. Due to the difficulty of inserting estimated annual values, we opted to use an average rate of reduced leakage. This rate was calculated by the difference between the arithmetic means of the simulated rates in the SL and of the calculated rates of reduced leakage. The resulting rate (0.000156) was then inserted into the calculation such that this value was deducted from the rate of deforestation simulated for each year (Table 2).

A rate of leakage for regeneration was not calculated; therefore, the formation of secondary vegetation is correlated with the deforested area. One expects that, with the reduction of the deforested area, there will be a reduction in the area occupied by secondary vegetation. This reduction in the area of secondary vegetation, in turn, would cause a reduction in the cutting of secondary vegetation.

2.5. Transition Functions (Expander and Patcher)

The transition functions guide the placement of patches in the landscape in accordance with the areas and the number of changes previously determined by the model. Expander acts exclusively in the expansion of previous patches of a given class of land cover. Patcher is responsible for the formation of new patches through a sowing mechanism. This process occurs when Patcher selects the nucleus cell of the new patch and then a specific number of cells is determined around this nucleus cell (Soares-Filho et al., 2002).

The model divides the number of cells to be modified between the two transition functions. In this case, it was established that 30% of the cells undergoing the transition forest → deforestation would be applied to the expander function and the remaining 70% to the patcher function. These values were defined during calibration processes. Different values for the patcher and expander functions were tested to compare the resulting spatial patterns of change. The values that visually indicated the best fit to the real spatial patterns of deforestation were 30% (expander) and 70% (patcher). Even though most of the patches are formed by the patcher function, these patches are usually placed near previously deforested areas and next to roads.

2.6. Calibration and Validation of the model

Fitting of the model parameters was done for the 2003 - 2008 period. In this stage, the coefficients of the weights of evidence and the transition rates were fit in order to obtain an adequate match between the simulated map and the reference (real) map. After the calibration stage the validation of the model was done. Validation has the intention of assessing whether the model used is consistently in agreement with the intended application (Rykiel, 1996).

DINAMICA EGO uses a fuzzy test for comparison of similarity, which is a modification of the method developed by Hagen (2003). This method considers the location of a change in the neighborhood of a central cell. Thus, depending on the size of the window of pixels representing the neighborhood of the central cell, the similarity between the maps (real and simulated) can vary from 0% to 100%, where 0% similarity indicates that the two maps are completely different and 100% indicates that they are identical (Soares-Filho et al., 2009; Walker et al., 2010).

The result of the spatial fit obtained using the similarity for multiple windows was 57.1% for the standard window size (5 × 5 cells). This percentage increases as the size of the window increases, reaching 73.8% for an 11 ×11-cell window size (Fig. S3). This method, only evaluates the spatial fit of the model. To verify the fit regarding the amount of change, the comparison was made between the number of cells in the real and simulated land-cover maps. The percentages of error for each class of use were: 0.14% (forest), 4.74% (deforestation) and 1.33% (secondary vegetation) (Table S2).

2.7. Analysis of the effectiveness of the Juma reserve

The scenarios simulated with the Juma reserve (SL and SRL) were used to analyze the advance of deforestation inside and outside of the reserve. The analysis was based on the map produced at each iteration of the model. This map was overlaid with the mask of the Juma reserve. This made only the area of the reserve visible, with the remaining area (buffer area) being masked so that the deforested area inside of the Juma reserve could then be quantified.

The quantification of deforestation in the area surrounding the reserve was done by overlaying the maps of simulated land cover in the 10-km buffer. This procedure yielded the number of cells in each class (forest, deforestation and secondary vegetation) in the area surrounding the Juma reserve. The overlaying was done for the 42 maps simulated in the SL and SRL. The data later were tabulated, and the ratio between the number of deforestation cells in the buffer area and in the reserve was calculated for each year. This allowed us to have a measure of how efficient the Juma reserve was in containing the advance of deforestation up to 2050. To evaluate the influence of the Juma reserve in the area along the AM-174 Highway, a 10-km buffer on either side of the highway was used (only for the segment that cuts through the reserve). Later, the maps of simulated land cover were overlaid with the buffer to analyze the evolution of deforestation along the highway. This analysis was done for all of the maps simulated in the three scenarios. It was possible in this way to evaluate the advance of deforestation in the area along the highway with and without the presence of the Juma reserve.

2.8. Estimates of biomass and carbon emission

The estimates of average biomass dry weight above and below ground for each type of forest were based on Nogueira et al. (2008). Estimates for the non-forest vegetation types were based on Fearnside et al. (2009b) and Olson (1983). The estimates of the initial supply of biomass were made by overlaying the map of original vegetation and the map of forest remaining in 2008. Prior to this procedure, the area of remaining forest (ha) was obtained for each type of vegetation. This area was then multiplied by the average biomass (per ha) corresponding to the type of vegetation. The carbon stock was obtained assuming that 1 ton (Megagram = Mg) of dry biomass contains 0.485 Mg C (Silva, 2007). To estimate the carbon emissions from cutting forest each year the overlaying was done between the land-cover maps for the years “t” and “t+1”, obtaining the number of forest cells that were deforested from one year to the next. The resultant map of deforested cells was then overlaid with the vegetation map to identify to the average biomass and the carbon stock of the deforested areas. This procedure, as well as the procedures to be described later, was done for each of the three scenarios simulated in this study.

2.8.1. Emission from cutting secondary vegetation

The methodology used to estimate carbon and emissions from cutting secondary vegetation was based on Fearnside and Guimarães (1996). This approach was chosen (1) due to the absence of specific studies on the biomass of secondary vegetation for the southern portion of the state of Amazonas and (2) because the main activity in this region is cattle ranching, which is similar to land use in the areas of Paragominas and Altamira, Pará, studied by Fearnside and Guimarães (1996). Thus, a significant part of the secondary vegetation formed and cut would be derived from abandoned pasture.

In the present study, the estimates of carbon emissions from cutting secondary vegetation were based on the average biomass (above and below ground) of secondary vegetation with five years of age, which was estimated by Fearnside and Guimarães (1996). Five years represents the time for half of the secondary vegetation of a given year to be cut based on the estimate by Almeida et al. (2010) that the half-life of secondary vegetation in Amazonia is 4.89 years.

The arithmetic mean of the biomass in Paragominas and Altamira (49.2 Mg ha^{-1}) was multiplied by the area (ha) of the secondary vegetation cut per year and, later, this value was multiplied by the carbon content of secondary vegetation (0.45) estimated by Silva (2007). Thus, an estimate was obtained of annual net emission from cutting secondary vegetation.

2.8.2. Carbon absorption by secondary vegetation

For the purpose of calculating net emissions, the carbon absorption by the secondary vegetation is determined from the growth rates of this vegetation derived by Fearnside and Guimarães (1996). The age structure of stands of secondary forest implied by patterns in Paragominas and Altamira is also assumed to apply to our study area. The growth rate of the total biomass (above and below ground) obtained (8.40 Mg ha^{-1} year^{-1}) was multiplied by the total area (ha) of secondary vegetation in a given year and, later, this value was multiplied by the carbon content of secondary vegetation (0.45) estimated by Silva (2007). Thus, an estimate was obtained of the annual absorption by the secondary vegetation in the landscape.

2.8.3. Inherited carbon emissions and absorptions

Calculations of the inherited emissions are necessary because the accounting of carbon emission from cutting forest was only done beginning in 2009 (the first year of the simulation) and because the estimates of carbon absorption by the secondary vegetation considered the total area of this vegetation present in 2009. Therefore, part of the mapped secondary vegetation in 2008 that remained in other years was also included, and the growth of this secondary vegetation represents an inherited absorption. Thus, both the absorption and the inherited emission need to be estimated to prevent a bias in the calculations of net emissions.

The inherited emissions were calculated from PRODES data on deforestation (1997, 2003 and 2008) and from the average biomass of forest (above and below ground), which was based on Nogueira et al. (2008). The calculations were based on a study by Fearnside (2002, 2003a), who used a scenario of three re-burnings over a 10-year interval, considering that the pasture is normally re-burned at intervals of 2 to 3 years in order to hinder the establishment of invading plants. In this scenario, the percentage of carbon emitted would be greater. Therefore, it was necessary to adjust the values of the lost biomass for the effect of the re-burnings. This biomass was multiplied by the carbon content of primary forest (0.485). The value of the inherited emission obtained was added to the other sources of emission from the cutting of forest and secondary vegetation.

2.8.4. Calculation of the annual balance of net emissions

The estimates of annual net emissions were obtained from the difference between the emission sources, that is, the sum of the emissions from cutting forest, cutting secondary vegetation and inherited emissions from deforestation in previous years, minus the sink from absorption by the secondary vegetation.

3. Results

3.1. Simulation of deforestation

In a general way, the results of the simulation in the three scenarios for the total study area were similar (Fig. 3). The reductions in forest cover in the total study area (Juma reserve + Buffer of 120 km) were 16.0% (baseline), 15.9% (SL) and 15.4% (SRL), as compared to the values in 2008. The similarity in the results of the baseline and the SL indicates that the deforestation prevented in the area of the Juma reserve in the SL was displaced to other areas of forest. In the SRL there was a reduction in deforestation by 3.2% in comparison with the baseline and by 2.9% in comparison with the SL (Table S3).

[Fig. 3 here]

However, when only the area of the Juma reserve is considered, the baseline scenario projected a reduction of 18.9% in forest cover as compared to 2008, whereas in the scenarios with the presence of the reserve (SL and SRL) this reduction was 7.1%. When the scenarios are compared, one finds that in the absence of the Juma reserve there would be a reduction of 62.5% in forest cover as compared to the scenarios with the reserve (Table S4).

Comparing the cumulative deforestation in the initial map (2008) with the simulated final map (2050), in the total study area, deforestation increased by 533.0% (baseline), 531.5% (SL) and 516.1% (SRL). If only the area of the Juma reserve is considered, this addition reaches 1,419.3% (baseline), 551.2% (SL) and 555.0% (SRL). For the area of secondary vegetation present in the total study area, there were increases of 414.7% (baseline), 410.9% (SL) and of 397.7% (SRL). In the area of the Juma reserve, these values were 5,729.7% (baseline), 1,627.0% (SL) and 1,500.0% (SRL) (Table S3 and Table S4).

The annual average deforestation in the total study area was similar in all scenarios: 349.9 km^2 (baseline), 348.7 km^2 (SL) and 338.5 km^2 (SRL). In the Juma reserve, approximately 25.1 km^2 of the forest cover was deforested per year in the baseline scenario and 9.4 km^2 in the SL and SRL. The annual average regenerated areas in the total study area were 106.9 km^2 (baseline), 105.5 km^2 (SL) and 102.8 km^2 (SRL). For only the Juma reserve, the areas regenerated annually were, on average, 9.6 km^2 (baseline), 2.2 km^2 (SL) and 2.1 km^2 (SRL). Regeneration in the SRL and SL was lower in comparison to the baseline scenario due to deforested area in these scenarios being smaller.

In the total study area 80.5 km^2 of secondary vegetation was cut in the baseline scenario, 79.3 km^2 in the SL and 77.4 km^2 in the SRL. In the Juma reserve itself, the averages of the area of secondary vegetation cut annually were 6.4 km^{2}in the baseline and 1.2 km^2 in the SL and SRL. It is important to emphasize that the area regenerated annually was superior to the area of secondary vegetation cut. This is due to the fact that there is no distinction in the model between the value of the cells of deforestation that are derived from the cutting of forest and those derived from the cutting of secondary vegetation.

The average percentage of the cells of secondary vegetation that had remained uncleared in the total study area for 30 iterations, and later were transformed into forest cells after this period, was 7.2% (22.2 km^2) in the baseline scenario, 7.6% (23.2 km^2) in the SL and 7.4% (22.4 km^2) in the SRL. In the Juma reserve, these values were 4.8% (0.6 km^2) in the baseline scenario, 25.9% (1.9 km^2) in the SL and 20.3% (1.8 km^2) in the SRL.

With the presence of the Juma reserve there was a reduction in deforestation and the cutting of secondary vegetation. Thus, most of the secondary vegetation that was present inside of the reserve at the beginning of the simulation remained unchanged throughout the time period, resulting in a regenerated area that was larger in the SL and SRL in comparison with the baseline.

3.2. Evaluation of the effect of the leakage in the projected scenarios

From the comparison of the number of cells between the maps (2050) in the baseline scenario and the SL, the corresponding number of cells of leakage for each class was estimated. Thus, in a possible scenario without leakage, the number of cells of forest, deforestation and secondary vegetation in the interior of the Juma reserve would have to be the same as that in the SL. In turn, in the external area (excluding the area of the Juma reserve), the number of cells of each class would have to be the same as that in the baseline. Based on this information the percentage of leakage of deforestation was 92.7% in the SL and 27.6% in the SRL. Thus, the simulation of the SRL had a reduction by 65.1% (6,852 cells) in leakage in comparison to what was simulated in the SL (Table S5).

3.3. Quantification of deforestation inside and outside of the Juma reserve

The scenarios showed that up to 2050 the cumulative deforestation in the area around the Juma reserve was 2.0 (SL) and 2.1 (SRL) times greater than that inside the reserve. Due to the deforested area being larger in the area surrounding the reserve, the formation of secondary vegetation also was greater. The proportion of the area occupied by secondary vegetation was 4.0 (SL) and 4.4 (SRL) times greater in the surrounding area than it was inside the reserve (Fig. 4a and 4b). The proportions of the area occupied by roads projected by the model for the area surrounding the Juma reserve were 2.5 (SL) and 2.6 (SRL) times larger in comparison to the internal area of the reserve (Fig. 4c). In this area, most of the deforestation was along the AM-174 Highway.

[Fig. 4 here]

The results of the simulation also indicated that with the presence of the Juma reserve there was an inhibition of deforestation in the area along the AM-174 in a 10-km wide strip on each side of the highway. However, this inhibition only occurred in the stretch of the highway located inside of the reserve. Over the 42-year period there was a reduction in forest cover by 42.5% (581.4 km^2) in the baseline scenario, 24.3% (332.8 km^2) in the SL and 25.6% (350.6 km^2) in the SRL. In addition, a reduction in the number of secondary roads projected by the model was detected when compared with the baseline: 39.7% (31.1 km^2) for the SL and 34.0% (26.6 km^2) for the SRL.

3.4. Estimates of carbon emissions and stocks in the simulated scenarios

The carbon stock present in 2008 in the total study area was estimated at 1.63 Pg C; considering only the Juma reserve, this stock was estimated at 0.10 Pg C. The initial (2008) stock estimated for the total study area underwent reductions by 15.7% (0.26 Pg C) in the baseline scenario and the SL and by 15.2% (0.25 Pg C) in the SRL. In the area of the Juma reserve reductions by 18.6% (0.02 Pg C) of the initial stocks in the baseline and by 7.1% (0.01 Pg C) in the SL and SRL were estimated (Fig. 5).

[Fig. 5 here]

Fig. 6 indicates the estimates of net emissions for the total study area and Juma reserve. Comparing the baseline and the SRL shows a reduction of 3.3% (8.5×10^6 Mg C) in carbon emissions. For the SL and SRL, this reduction was 2.9% (7.3×10^6 Mg C). If only the area of the Juma reserve is considered, the creation of the reserve reduced the carbon emission by 61.8% (11.6×10^6 Mg C) up to 2050.

[Fig. 6 here]

4. Discussion

4.4. Projections of baseline scenarios

The projection of the baseline scenario up to 2050 demonstrated that deforestation in the Juma reserve will not advance in such a way as to completely compromise the forest cover in the reserve. This can be justified by the fact of that most of the simulated deforestation was located in areas where there had already been intense anthropogenic activity, such as those near the town of Apuí and in areas near the BR-230 Highway (Graça et al., 2007). In accordance with the model, these areas are considered to be more attractive to deforestation. Therefore, there was already a historical trend that favored deforestation in this region, mainly due to pressure from the expansion of agriculture and ranching (Cepal, 2007; Carrero and Fearnside, 2011; Cenamo et al., 2011). Moreover, population growth in the municipality of Novo Aripuanã is moderate, the main uses of the land being subsistence agriculture, forest extractive activities and fishing. Deforestation for opening pastures occurs near the town of Apuí and in the

Acari settlement project, which is linked to the population of Apuí (Cenamo et al., 2011).

The baseline scenario of the present study demonstrated that up to 2050 there would be a reduction of 18.9% (1,052.4 km^2) in the forest cover of the Juma reserve. This result differs substantially from the baseline scenario used by the Juma REDD project (IDESAM, 2009), which is based on the business-as-usual (BAU) scenario simulated by Soares-Filho et al. (2006) for the Amazon Basin (Fig. 7). The model developed by these authors (SimAmazonia) projected a reduction in forest cover by 80.7% (4,512.0 km^2) up to 2050 in the Juma reserve. The SimAmazonia projection of deforestation is 4.3 times higher than the projected deforestation for the baseline scenario in the present study.

[Fig. 7 here]

The main reason for this difference is that the annual increment of deforestation simulated by Soares-Filho et al. (2006) for the Juma reserve was influenced by the area of remaining forest present in a sub-region with a total area of 1,647,690 km^2, or 40% of the originally forested area of Brazilian Amazonia. These authors used the concept of sub-regions defined from a socio-economic stratification, where the state of Amazonas and parts of the states of Pará and Mato Grosso with considerable areas of forest were grouped into a single sub-region. In this sub-region, approximately 89.9% of the forest cover was intact in the initial landscape (2001). The annual area deforested was calculated on the basis of the extent of remaining forest in this sub-region (i.e., multiplying an annual rate, expressed as a proportion, times the area of forest). However, the spatial allocation of the deforested cells was concentrated in the southeastern and northeast portions of the sub-region because these were the areas where there had been previous deforestation, in addition to being where deforestation would be influenced by paving highways such as the BR-319, BR-230 and BR-210.

Another difference between our baseline result and the one used in the Juma REDD project is that the REDD project excludes certain areas of the reserve, such as areas deforested before the beginning of the project, private properties, areas under the influence of the AM-174 Highway, community-use areas and areas with non-forest vegetation (IDESAM, 2009). The project design document of the Juma REDD project (http://www.fas-amazonas.org/pt/secao/projeto-juma) describes an estimate of the reduction of forest cover by 65.8% (3,661.5 km^2) by 2050.

It is also important to emphasize that the model by Soares-Filho et al. (2006) indicates a gradual increase in the rates of deforestation in the sub-region in question. This increase was due to the paving of BR-319 Highway (2012 and 2018) and stretches of the BR-230 Highway (2025) (Soares-Filho et al., 2006). The major differences occur after 2030, when the effects of these events in the SimAmazonia model are reflected in the Juma area. The paving of the highways and associated projection of secondary roads contributed to the increase in deforestation in the area of the Juma reserve. The present study did not consider the paving of highways, only considering the construction of the AM-360 and BR-174 Highways. These roads caused a moderate increase in deforestation rates. Thus, the effect of these roads did not cause drastic alteration in the forest cover of the Juma reserve.

The speed with which deforestation occurs in the Juma reserve and surrounding area is the major difference between our baseline result and that of Soares-Filho et al. (2006). Given more time, our model also shows massive forest loss. When our model is run to the year 2100, the result is qualitatively similar to the Soares-Filho et al. (2006) result for 2050 (Fig. S4). The major factors affecting the value attributed to avoided emissions through reserve creation are the timing of the emissions (and of avoided emissions) and the value attached to time by means of discounting and the choice of a time horizon (Fearnside, 2009). When deforestation in the landscape surrounding a reserve reduces available forest to negligible amounts, as would occur by 2100 in our model (Fig. S4), the carbon benefits that had been lost to leakage over the preceding years will be recuperated because deforestation that would eliminate the forest in the reserve under the baseline (no reserve) scenario will be prevented from occurring (Fearnside, 2009).

Ecological observations made at different spatial scales can imply widely differing results; the coarser the spatial resolution used in the modeling, the greater the chance of having errors from distortions and losses of information (Yeh and Li, 2006). Models constructed in DINAMICA EGO are based on the cellular automata mechanism, where the state of a cell is determined as a function of the neighboring cells and the spatial probability of a cell changing from one state to another is calculated for each cell in accord with the transitions specified in the land-cover map. Then, depending on the spatial resolution used, the allocation of the cells in the areas that are most favorable for each transition can be modified in the probability map, consequently the landscape dynamics of the simulated scenarios will be different.

The input maps used in the model by Soares-Filho et al. (2006) had spatial resolutions of 1 and 2 km, and the simulated maps had a spatial resolution of 1 km. IDESAM (2009) mentions that the difficulty of having used this scenario with 1 × 1-km cells is that the original size of the attributes does not correspond to the reality in the area, which makes it difficult to delimit the area of forest with potential to generate REDD carbon benefits.

Although the spatial resolution used in the current study was 250 m, loss of information can still be detected. For example, areas of secondary vegetation were mapped with Landsat-5 TM images with a spatial resolution of 30 m, which was suppressed when degrading the images to a resolution of 250 m.

The projections made by the SimAmazonia model (Soares-Filho et al., 2006) were important in demonstrating the possible trajectories of Amazonian forest at a regional scale. However, it is important to emphasize that the use of this approach at a local scale, as in the case of a reserve, can be dangerous as a means of estimating the reductions of carbon emissions in REDD projects because it can overestimate deforestation rates.

If the baseline scenario overestimates the rate of deforestation in the area of the project, only a part of the intervention would in fact be additional, and the purchaser of the environmental service would pay for a reduction in deforestation that is not real (e.g., Wunder et al., 2008).

4.5. Effectiveness and leakage in the Juma reserve

In a general way, studies that evaluate the effectiveness of protected areas compare the impacts of the anthropogenic activities (deforestation, forest fires, logging, hunting and predatory fishing) inside and outside of the boundaries of a reserve (Bruner et al., 2001; Ewers and Rodrigues, 2008). Thus, if anthropogenic pressure is lower inside the reserve in comparison with the surrounding area, this means that the restriction of use in this area has a positive impact for conservation (Ewers and Rodrigues, 2008). However, the reduction of deforestation inside of a reserve can later contribute to the acceleration of deforestation in other areas that are important for conservation of biodiversity located near the reserve (effect of leakage). Along these lines, strategies to quantify and to prevent leakage in REDD projects have been proposed in the context of mitigating climatic change (more details on this in Wunder, 2008).

In the present study, due to the stochastic characteristics of the models based on cellular automata (which produce variations in each simulation) and the fact the average rate of leakage obtained from the SL was used, it was not possible to simulate a scenario 100% without leakage. It can also be observed that the deforestation stemming from leakage was not concentrated in the area surrounding the reserve (10-km buffer). In this strip, the areas deforested in the SL and SRL were similar; therefore, it is assumed that the deforestation derived from the effect of leakage was allocated to other areas in the landscape.

Scenarios with leakage have been simulated in other studies (Aguiar, 2006; Vitel, 2009). In the simulation done by Aguiar (2006) using the CLUE modeling framework, the demand for land (deforestation rate) was constant. Therefore, the creation of protected areas did not influence the overall rates of deforestation and only induced the displacement of deforestation to other areas that did not have any type of use restriction (100% leakage). Aguiar (2006) argued that scenarios with leakage can, in fact, occur; therefore the effect of local policy decisions can be reflected in actions that are not necessarily beneficial in other areas. This, however, depends on the perception of the actors in relation the restrictions and opportunities created for public policies. Vitel (2009), using the AGROECO model, simulated different scenarios with and without the creation of sustainable-use and integral-protection reserves in the municipality of Lábrea (southwestern Amazonas). This study demonstrated that, with the creation of an integral-protection reserve, the deforestation that would occur in this area in the absence of the reserve was displaced to areas inside a sustainable-use reserve, which is considered to be one of the categories of reserve that is most vulnerable to deforestation. Thus, protecting areas that have a greater restriction on use, as in the integral-protection reserves and indigenous lands, tends to be more efficient as compared to the sustainable-use reserves (Clark et al., 2008). On the other hand, the greater political support for creation of sustainable-use reserves gives them an important conservation role due to the critical need for substantial expansion of protected areas before increased deforestation pressure renders reserve creation impractical (Fearnside, 2003b).

The projections elaborated in the current study demonstrated that most of the deforestation inside of the Juma reserve was located next to roads (side roads and the AM-174 Highway that cuts through the reserve) and in areas that were previously deforested. This result agrees with the analysis by Brandão Jr. et al. (2007) relating deforestation to official and unofficial roads in Amazonia. These authors found that deforestation declines exponentially with increasing distance to roads. Souza Jr. et al. (2005) suggest that the identification of areas that are susceptible to the expansion of illegal roads could be an important criterion for prioritizing the creation of protected areas.

4.6. Estimates of carbon emissions in the projected scenarios

IDESAM (2009) estimated a stock in the Juma reserve in 2006 of 0.07 Pg C. The present study estimated a stock of 0.10 Pg C in 2008. The difference is due to the fact that the estimate of the carbon stock used by IDESAM (2009) was an average based on the report by MCT (2004) and the study by Nogueira et al. (2008), while in the present study the estimate for each forest type was based only on Nogueira et al. (2008). The MCT (2004) report underestimates biomass for a variety of reasons (Fearnside, 2008b). Areas with non-forest vegetation, private properties (areas with legal title), areas around the communities and the area of influence of the AM-174 Highway were excluded from the accounting of the carbon stock by IDESAM (2009), while in the present study all of the forest cover in the reserve, as well as the non-forest vegetation, was included in the accounting.

In the total study area, the annual averages of the simulated emissions were 6.10 × 10^6 Mg C (baseline), 6.07 × 10^6 Mg C (SL) and 5.90 × 10^6 Mg C (SRL). These values correspond to 6.9% (baseline), 6.8% (SL) and 6.7% (SRL) of the emissions from fossil fuel burning in Brazil in 2005 (88.7 × 10^6 Mg C) (MCT, 2010). In the area of the Juma reserve, the annual average emission in the baseline scenario corresponded to 0.5% (0.45 × 10^6 Mg C) of the fossil fuel emissions in Brazil in 2005. In the scenarios with creation of the reserve the emissions corresponded to 0.2% (0.17 × 10^6 Mg C) of Brazil's fossil-fuel emissions.

Fearnside (2008c) estimated the emissions for deforestation in 2007 in Brazilian Amazonia at 162.5 × 10^6 Mg C (11,224 km^2). This estimated rate of deforestation was based only on the Landsat-TM scenes considered to be critical (74 images) in that period (INPE, 2010). The simulated annual average emissions in the present study correspond to 3.8% (baseline), 3.7% (SL) and 3.6% (SRL) of the carbon emissions of Amazonia in 2007. For the Juma reserve these values corresponded to 0.3% (baseline) and 0.1% (SL and SRL).

We emphasize that the inherent uncertainty in estimates of forest biomass and of the corresponding emissions per hectare deforested (see supplementary online material) are separate from those inherent in the simulation of how deforestation proceeds with or without the reserve (see supplementary online material). The magnitude and location of deforestation in the simulated scenarios are important in elucidating the importance of how deforestation rates are calculated (for example in the baseline used for the Juma REDD project versus our model), and in identifying the roles of factors such as leakage in the climate benefits of the reserve over the time period considered. These conclusions would not change were the true biomasses of the forests in the area different from the estimates we used. The deforestation simulations have uncertainties in the choice of model structure and in the quantification of the parameters, but we believe that our choices compare well with other models, such as that used by the Juma REDD project.

In the case of our model, deforestation rates reflect behavior patterns in the study area over the 2003-2008 period, which was not a period of significant enforcement effort. In the period since 2008 this part of Amazonia has also not been a major focus of enforcement. These factors could change in the future in either direction. Future unknowns include the relative importance of environmental concerns in Amazonian development policies. Very significant legislative setbacks for maintaining Amazon forest occurred in 2011 and 2012, including repeated victories of the "ruralist block" (representatives of large landholders) in weakening Brazil's "Forest Code" (a 1965 law requiring maintenance of defined areas of forest in private properties) and in restraining the authority of federal agencies responsible for enforcement of environmental regulations and for creating protected areas (see Fearnside, 2010; Metzger et al., 2010; IPEA, 2011; CBDFDS, 2012). The inherent uncertainty in assumptions regarding future levels of governance should be recognized in interpreting the results of this or any other model that represents land-use change over a period of decades.Projections of deforestation produced from stochastic models are simplified representations of a complex system and, therefore, the results must only be seen as probable possibilities. The AGROECO model was developed with the intention of helping to understand of changes in land cover in the Amazon region. Thus, despite the limitations of the model, the scenarios can contribute to evaluating the methodology currently used in REDD projects in the state of Amazonas.

As mentioned at the outset, the place of REDD in global-warming mitigation is an extremely controversial topic. The results of the present study will undoubtedly be interpreted differently by opposing camps. Anti-REDD advocates would conclude that the Juma REDD project's unrealistically high claims of carbon benefits from the reserve over the project period show that REDD should be excluded from crediting under the United Nations Framework Convention on Climate Change, while REDD proponents would point to our study's advances in modeling deforestation and the indication of climatic benefits over a long time horizon as arguments in favor of this form of mitigation.

5. Conclusion

The projections demonstrated a reduction in carbon emissions from deforestation due to the presence of the Juma reserve. However, up to the time horizon used in the modeling (2050), the carbon benefits would be modest and are substantially less than what was calculated in the Juma REDD project. This indicates the need for increased care in modeling baselines for calculating the carbon benefits of REDD projects if the generation of "hot air" (non-additional credit) is to be avoided.

As deforestation in the region progresses, the Juma reserve will play an increasingly important role in carbon storage and the maintenance of other environmental services. The amount and timing of leakage must be considered and quantified; for the 42-year time horizon considered in this study, leakage would reduce the net carbon benefit of the reserve, but reserve benefits would be greater over a longer time horizon.

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Figure Legends

Fig. 1. Location of the study area. The limits of the total study area are shown by the circular buffer.

Fig. 2. Flowchart showing the stages in the study.

Fig. 3. Maps of the landscape in 2050 under the three scenarios: baseline, SL and SRL. The upper map in each panel shows the landscape in the total area of the simulation, and the lower maps shows the Juma reserve.

Fig. 4. Areas deforested and regenerated inside and outside of the Juma reserve up to 2050 in **(a)** scenario with leakage (SL), **(b)** scenario with reduced leakage (SRL) and **(c)** area occupied by roads inside the Juma reserve and in the surrounding area up to 2050.

Fig. 5. Estimate of the carbon stock present in 2008 and after 42 years (2050) under the three scenarios in total study area and Juma reserve.

Fig. 6. Estimate of net emissions up to 2050 for each scenario in the total study area and the Juma reserve.

Fig. 7. Maps in the upper panel show the business-as-usual scenario by Soares-Filho et al. (2006) used as the baseline for the Juma REDD project; maps in the lower panel show the baseline scenario in the present study.

Table 1

Maps elaborated to insert as input data in the AGROECO model.

Input data	Source	Description of methods
Maps of land cover (2003 and 2008)[*]	PRODES (INPE, 2010)	The map (2003) was produced from the reclassification of the data from the attribute table of the mosaic of the state of Amazonas (2008). Thus, the cumulative deforestation up to 2003 was grouped into a single class (deforestation). The deforestation that occurred after 2003 was grouped with the “forest” class. The same methodology was used to construct the map of land cover in 2008. Mapping of secondary vegetation was done using the methodology developed by Graça and Yanai (2008). Later, the “secondary vegetation” class was incorporated into the categorical map of land cover using algebraic expressions in DINAMICA EGO (Fig. S2).
Map of static variables	▪ Distance to rivers (PRODES); ▪ Altitude and Slope (SRTM); ▪ Vegetation and Soil (IBGE); ▪ Protected areas (SDS, Greenpeace and ISA); ▪ Distance to main and secondary roads (updated from the map of roads by CSR/UFMG);	The “create cube map” operator was used to compile these different maps into a single file. The calculation of distance is performed by a DINAMICA EGO “functor,” which receives input from a categorical map and generates a map of distance bands (shortest distance) between in the cells of each class (Soares-Filho et al., 2009).
Maps of friction and attractiveness	In this study, areas of forest without reserves were susceptible to road construction, followed by sustainable-use reserve, integral-protection reserve and indigenous lands.	The friction map is used to obtain the least-cost pathway to construct new roads. The cost is proportional to the cell value. Attractiveness map assists the calculation of destination cells to construct roads taking into account measure of attractions determined on attractiveness map (Soares–Filho et al., 2004, 2006, 2009). These maps assist the performance of the road-construction module. Thus, the roads are automatically placed in accordance with the level of attractiveness and the cost of constructing a road.

[*] The map for 2003 was used in the calibration and the map for 2008 in simulating the scenarios up to 2050**.**

Abbreviations:

CSR/UFMG: Center for Remote Sensing of the Federal University of Minas Gerais

IBGE: Brazilian Institute for Geography and Statistics

ISA: Socio-Environmental Institute

PRODES: Program for the Calculation of Deforestation in Amazonia

SDS: State Secretariat for the Environment and Sustainable Development of Amazonas

STRM: Shuttle Radar Topography Mission

Table 2. Equations used in the study.

Rates	Equation and values used
Deforestation$_{year}$[*]	$= \dfrac{(AFS_{year} \times 0.02333) + (\text{Forest Outside of the } AFS_{year} \times 0.00023604)}{(AFS_{year} + \text{Forest Outside of the } AFS_{year})}$
Regeneration$_{year}$[*]	Constant = 0.0134
Cutting of secondary vegetation $_{year}$[*]	Constant = 0.125
Rate without leakage$_{year}$	$= \dfrac{(\text{Cells of forest cut (SL)}_{year} - \text{Cells leaked}_{year})}{(\text{Cells of forest (SL)}_{year} + \text{Cells leaked}_{year})}$
Deforestation$_{year}$ for SRL[*]	= Deforestation rate$_{year}$ − 0.000156

[*] Equations inserted in the Vensim software.

Figure 1

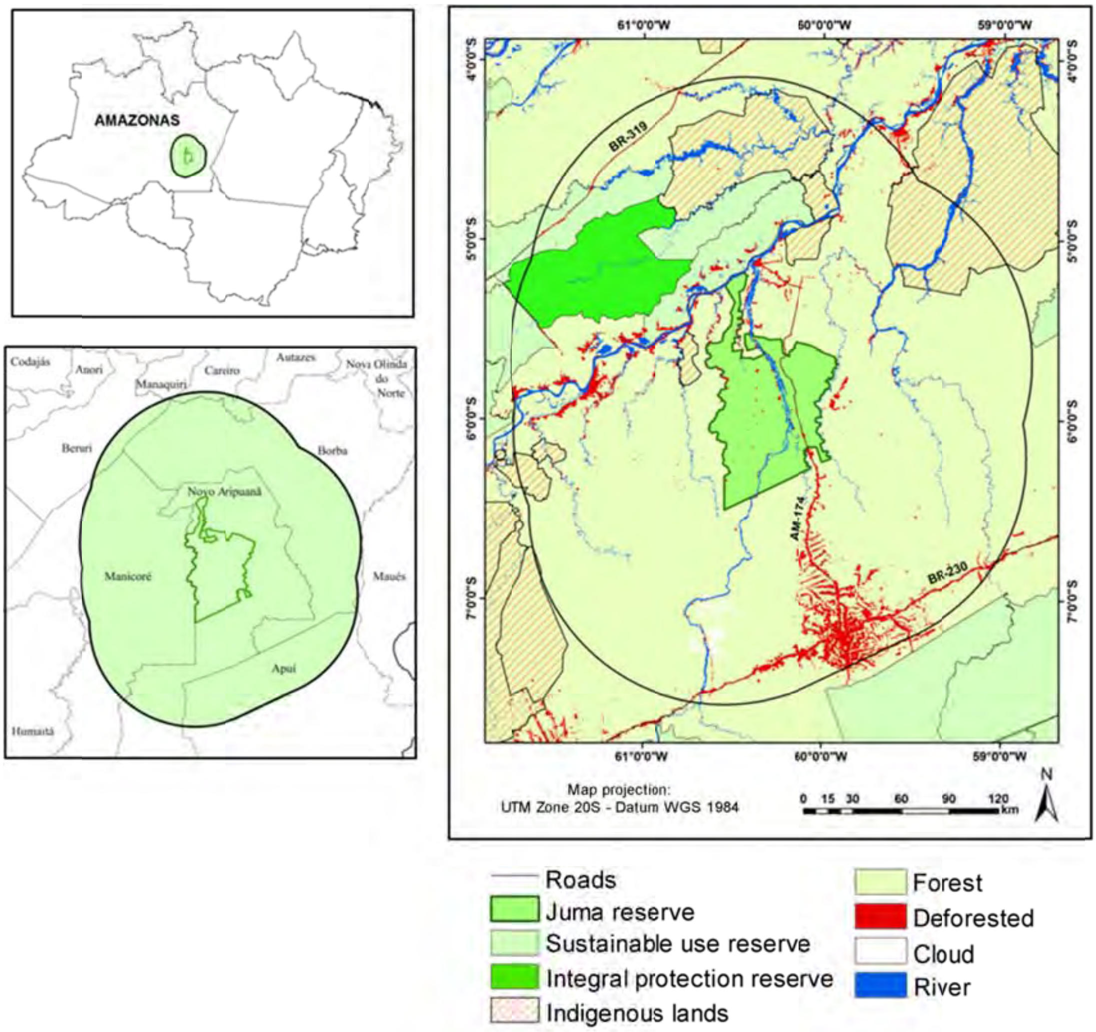

AMAZONAS
Codajás
Anori
Manaquiri
Careiro
Autazes
Nova Olinda do Norte
Beruri
Borba
Novo Aripuanã
Manicoré
Maués
Apuí
Humaitá
61°0'0"W
60°0'0"W
59°0'0"W
4°0'0"S
5°0'0"S
6°0'0"S
7°0'0"S
BR-319
AM-174
BR-230
Map projection:
UTM Zone 20S - Datum WGS 1984
0 15 30 60 90 120 km
N
Roads
Juma reserve
Sustainable use reserve
Integral protection reserve
Indigenous lands
Forest
Deforested
Cloud
River

Figure 2

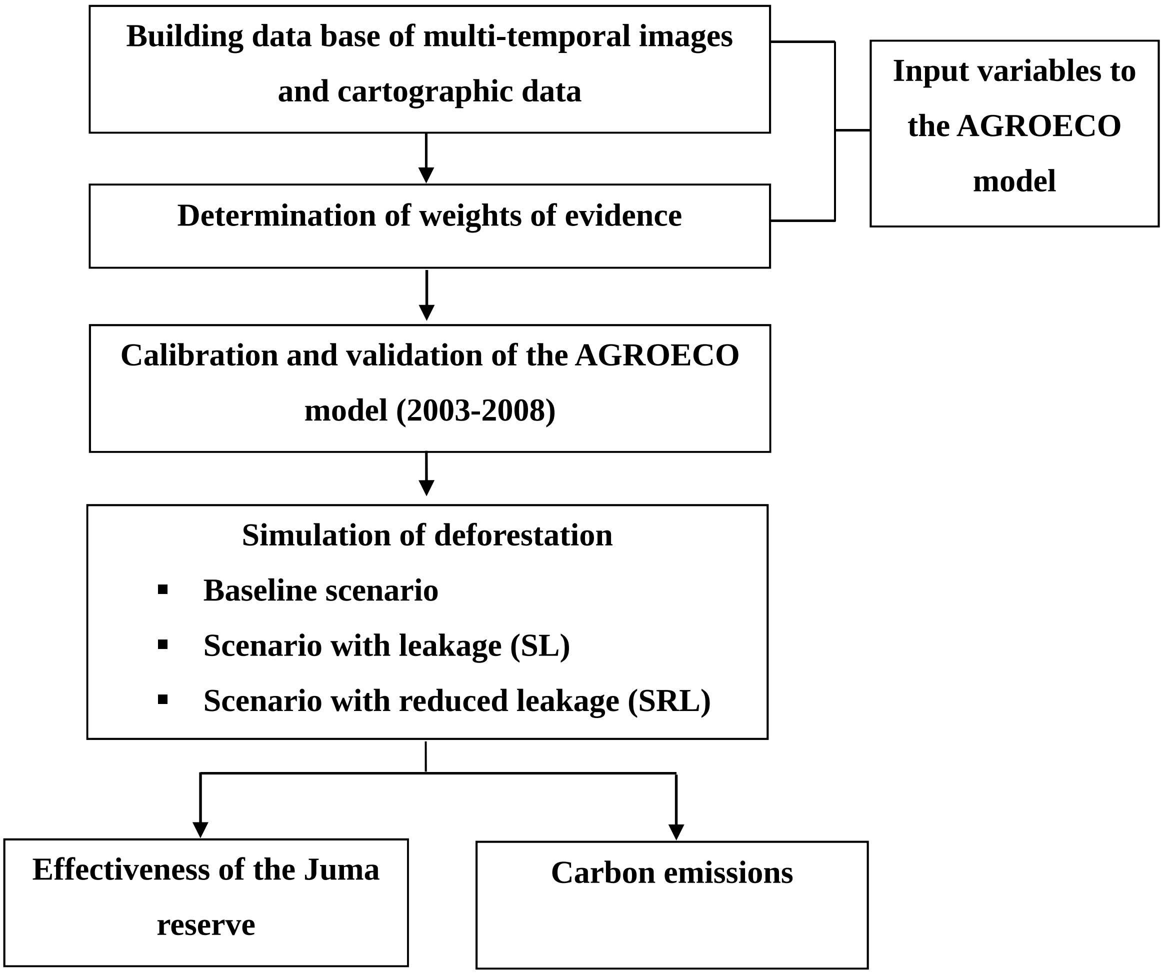

Building data base of multi-temporal images and cartographic data
Determination of weights of evidence
Input variables to the AGROECO model
Calibration and validation of the AGROECO model (2003-2008)
Simulation of deforestation
Baseline scenario
Scenario with leakage (SL)
Scenario with reduced leakage (SRL)
Effectiveness of the Juma reserve
Carbon emissions

Fig. 3

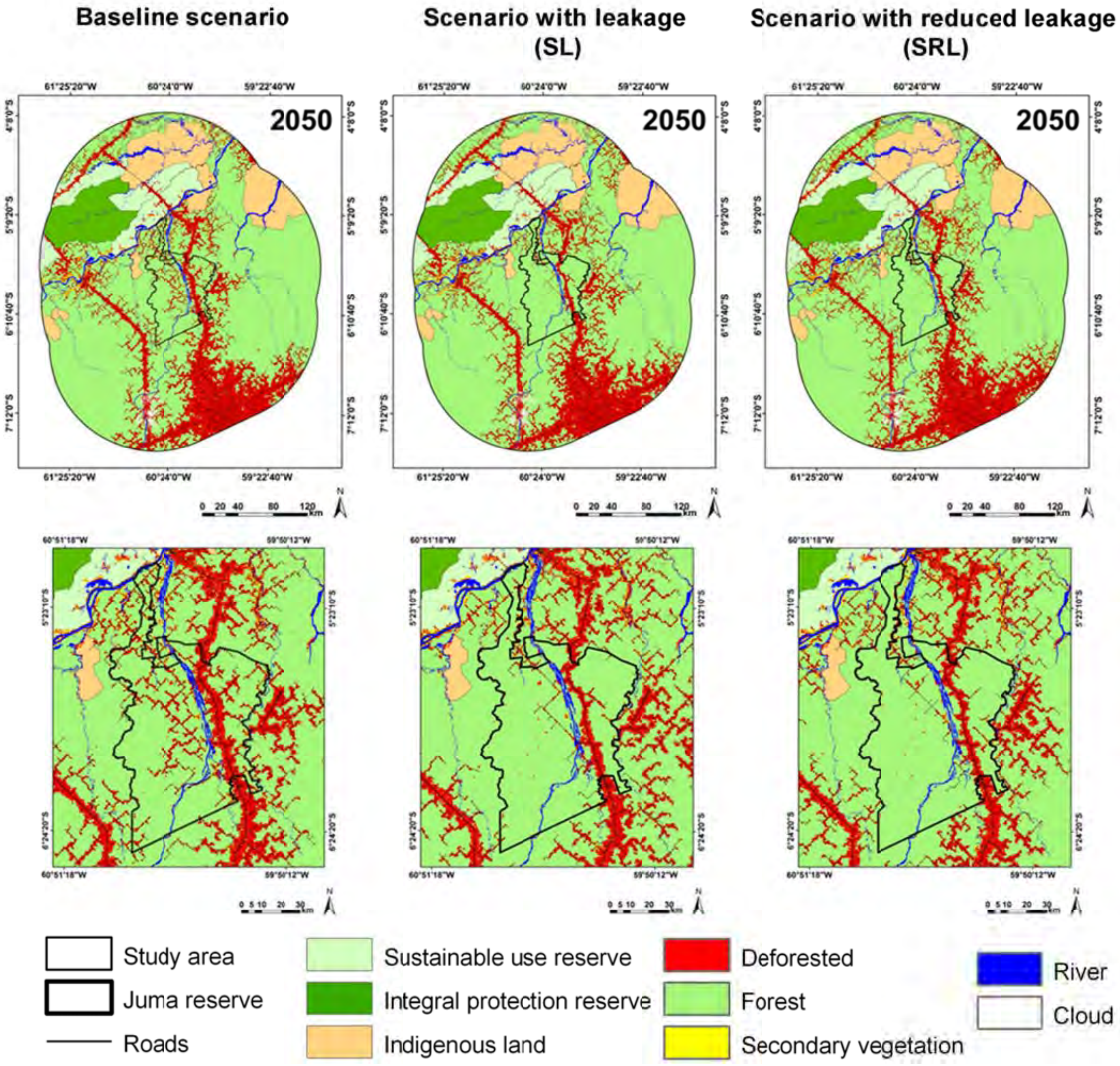

Baseline scenario
Scenario with leakage (SL)
Scenario with reduced leakage (SRL)
2050
61°25'20"W
60°24'0"W
59°22'40"W
4°8'0"S
5°9'20"S
6°10'40"S
7°12'0"S
0 20 40 80 120 km
N
60°51'18"W
59°50'13"W
59°50'12"W
5°23'10"S
6°24'20"S
0 5 10 20 30 km
Study area
Juma reserve
Roads
Sustainable use reserve
Integral protection reserve
Indigenous land
Deforested
Forest
Secondary vegetation
River
Cloud

Figure 4

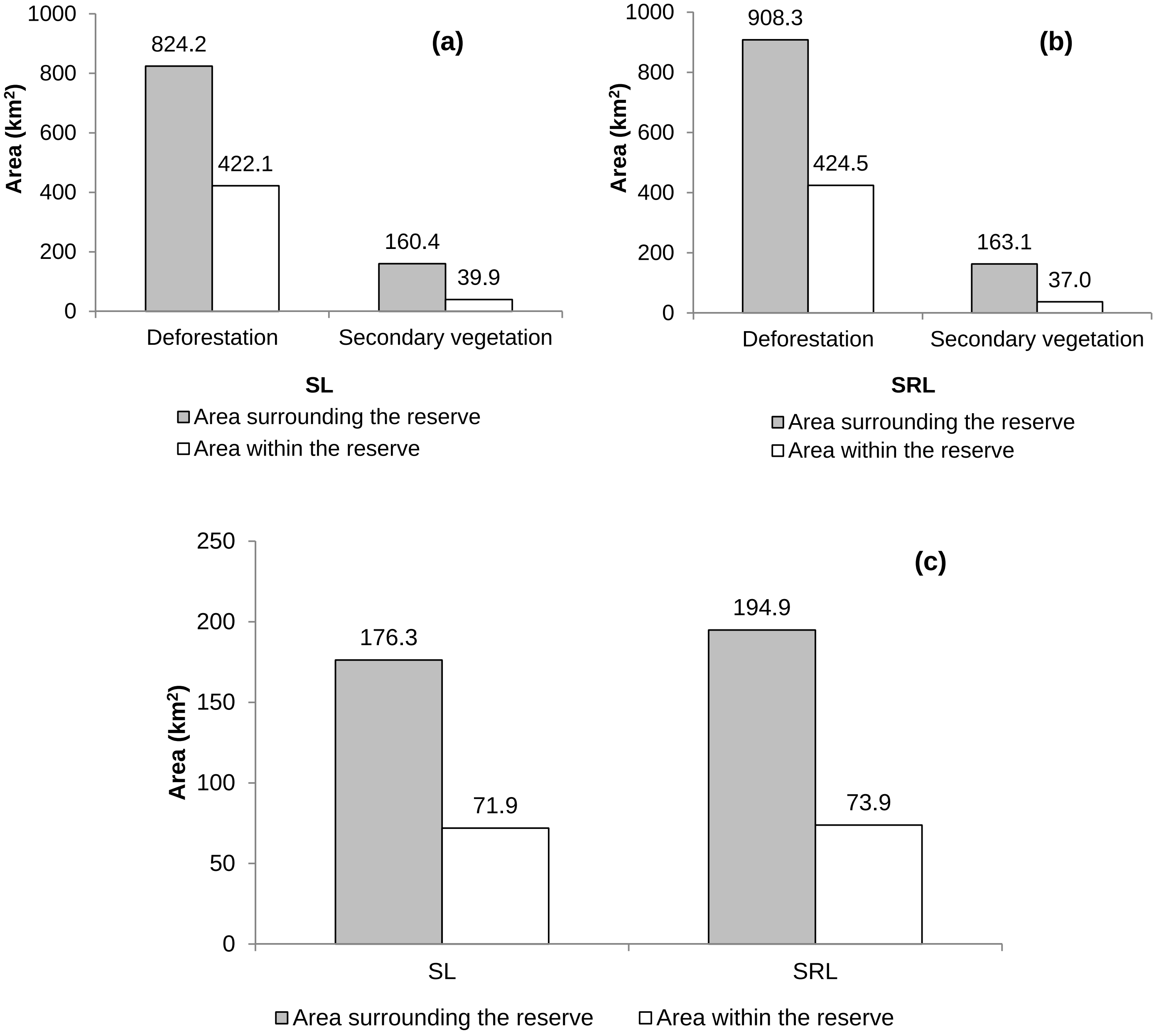

(a)
Area (km²)
1000
800
600
400
200
0
824.2
422.1
160.4
39.9
Deforestation
Secondary vegetation
SL
▨ Area surrounding the reserve
☐ Area within the reserve
(b)
Area (km²)
1000
800
600
400
200
0
908.3
424.5
163.1
37.0
Deforestation
Secondary vegetation
SRL
▨ Area surrounding the reserve
☐ Area within the reserve
(c)
Area (km²)
250
200
150
100
50
0
176.3
71.9
194.9
73.9
SL
SRL
▨ Area surrounding the reserve
☐ Area within the reserve

Figure 5

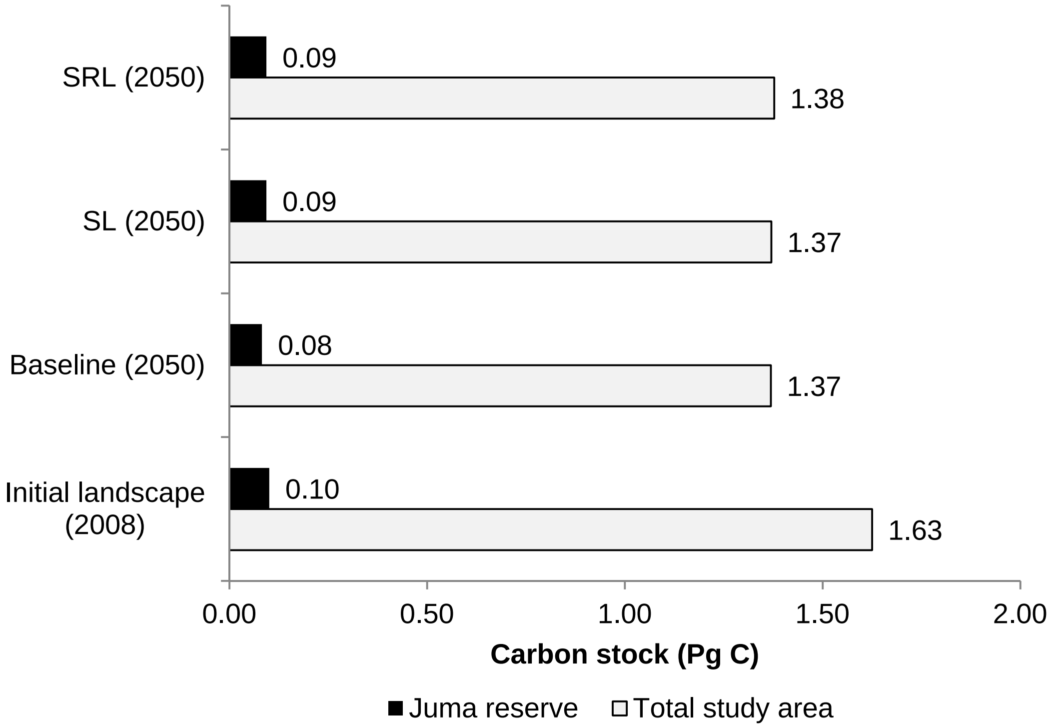

SRL (2050)
SL (2050)
Baseline (2050)
Initial landscape (2008)
0.09
1.38
0.09
1.37
0.08
1.37
0.10
1.63
0.00
0.50
1.00
1.50
2.00
Carbon stock (Pg C)
■ Juma reserve
□ Total study area

Figure 6

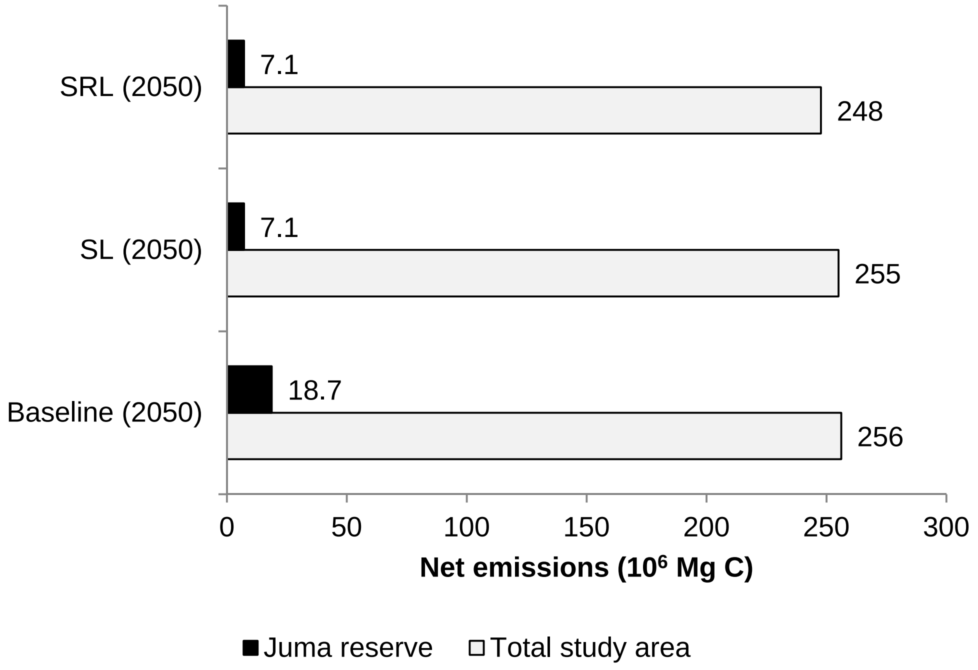
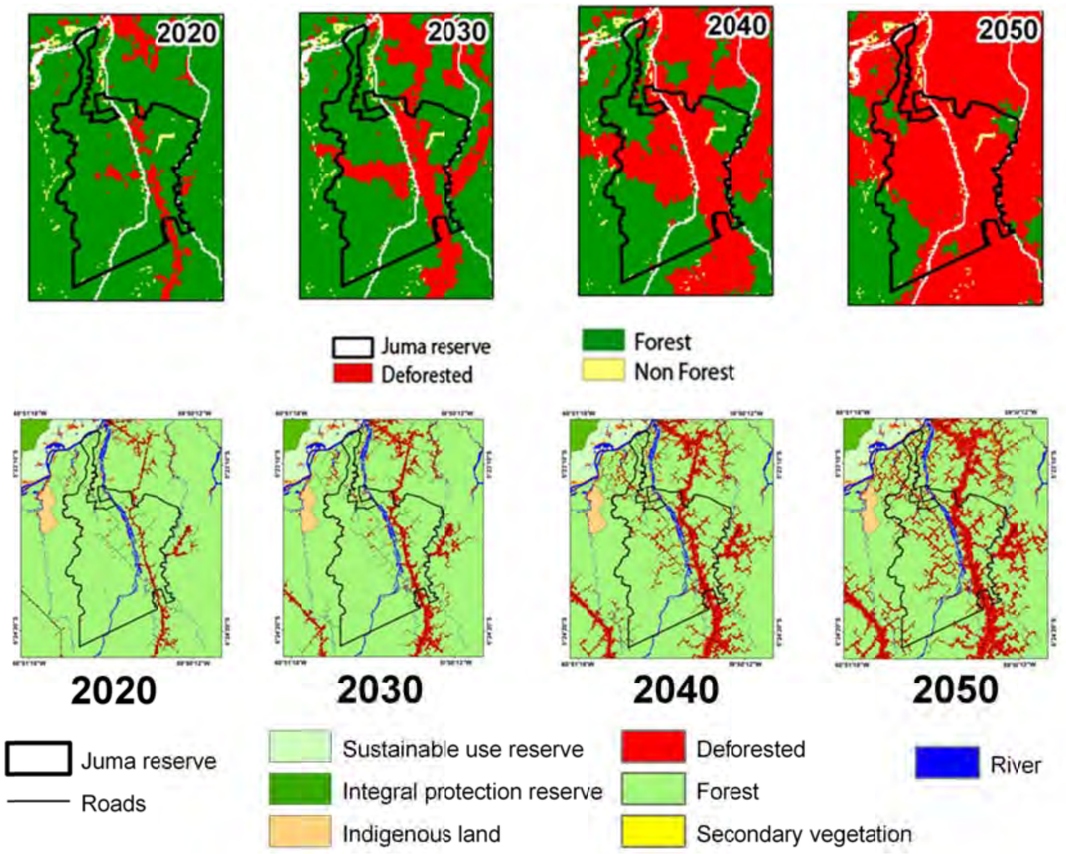

SRL (2050)
SL (2050)
Baseline (2050)
7.1
248
7.1
255
18.7
256
0
50
100
150
200
250
300
Net emissions (10^6 Mg C)
■ Juma reserve
□ Total study area

Fig. 7


2020
2030
2040
2050
Juma reserve
Deforested
Forest
Non Forest
2020
2030
2040
2050
Juma reserve
Roads
Sustainable use reserve
Integral protection reserve
Indigenous land
Deforested
Forest
Secondary vegetation
River

Supplementary Online Material

Avoided Deforestation in Brazilian Amazonia: Simulating the effect of the Juma Sustainable Development Reserve

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S1. Choice of the time interval for model calibration

The 2003-2008 period used to calibrate the model is, perforce, very short for a 42-year simulation. This implies uncertainty in the simulated results, especially for the last years of the simulated period. Yearly data are only available from 2000 onwards, but, in any event, prior to 2000 deforestation rates were minimal in the area due to its isolated location. Calibration could have begun in 2000 rather than 2003, but the results would have been almost the same as those from the period we chose. Average deforestation rate (expressed as the proportion of forest cleared annually) for the Juma reserve itself was constant at 0.0003 for periods to 2008 starting in 2000, 2001, 2002, or 2003. For the study area as a whole the average annual rates were 0.0011 for 2000-2008, 0.0012 for 2001-2008, 0.0013 for 2002-2008 and 0.0015 for 2003-2008.

*S.**2.** Independence of variables in the weights of evidence method*

In our experience, and in that of others who have studied Amazonian deforestation, the strongest predictors of deforestation activity are the distance to previously existing deforestation and the distance to roads (e.g., Laurance et al., 2002; Ferreira et al., 2005; Soares-Filho et al., 2004). These variables are highly correlated because most deforestation occurs near roads. However, in Amazonia the construction of new roads into areas with virtually no pre-existing deforestation represents an important feature of the overall process. These new roads have an influence on deforestation that is independent of the effect of previous deforestation, and therefore must be included in the model if the results are to be realistic. Distance to roads is represented by two variables, one for main roads and one including secondary roads. For the areas that have both roads and pre-existing deforestation, the inclusion of both the variables for distance to roads and for distance to deforestation will increase the weight given to their joint effect. This heavy weight results in modeled deforestation being concentrated along roads, which mirrors the pattern of real deforestation in the region. In other situations for which weights of evidence are used, such as mineral prospecting, this increased effect should be avoided (e.g., Agterberg and Cheng, 2002). In the development of the AGROECO model (Fearnside et al., 2009) trial runs without this heavy weighting for the effect of roads and pre-existing deforestation were found to result in a diffuse "popcorn" pattern of deforestation that is clearly not the normal pattern in the real world. These variables were therefore included in our model based on an *a priori* decision. Besides these variables, a pair-wise comparison of "main roads" with "all roads" indicated some correlation (Cramer's index = 0.63; joint information uncertainty = 0.53). For "soil" and "vegetation" only the Cramer's index value (0.46) indicated some correlation, the value of joint information uncertainty being only 0.16. For other variables, conditional independence was obeyed. Weights of evidence only influence the location of deforestation, not the amount of deforestation.

S.3. Validation of the model using fuzzy similarity

The minimum fuzzy similarity value found in the present study (73.8% for a window size of 11 × 11 pixels) is acceptable because the idea of using this procedure consists of not discarding models that do not exactly match in a cell-by-cell comparison, but that show good spatial approximation in the vicinity of the cell (Soares-Filho et al., 2002). Furthermore, some shapes of real deforestation patches produced by farmers could not be reproduced in the simulation because some types of patch geometry cannot be replicated with the transition functions currently available in DINAMICA EGO (Ximenes et al., 2011).

Other studies in the Amazon region have used fuzzy similarity to validate DINAMICA EGO models. Ximenes et al. (2011) found a fuzzy similarity index of 90.4% (11 × 11 pixels) using a three-year period (1997-2000) and spatial resolution of 120 m in the municipality of São Felix do Xingu (Pará state) and surrounding area. The spatial approximation within a cell neighborhood (window size) was high because only the expander function was employed in the model. Maeda et al. (2011) simulated the expansion of agricultural and cattle raising activities in a watershed on the fringes of the Xingu National Park in northeastern Mato Grosso. These authors calibrated a model using a time period of five years (2000-2005) and pixel size of 100 m. They found a minimum fuzzy similarity of approximately 45% (11 × 11 pixels). This study used the same time period as our study. Ramirez-Gomez (2011) found a fuzzy similarity value similar to that found in our study. This author assessed the influence of environmental drivers on forest cover change in eastern Suriname using a spatial deforestation model. A spatial resolution of 30 m was used. A value of 74% was found for fuzzy similarity using a four-year period (2005-2009) with a window size of 11 × 11 pixels.

S.4. Uncertainty of carbon emissions in the projected scenarios

Estimates of biomass and greenhouse-gas emissions have considerable uncertainty, the magnitude of which is incompletely quantified. This is true of all (we repeat: all) estimates of these quantities in tropical forests. However, we believe that our estimates are more reliable than others available in the literature due to the large number of 1-ha forest volume measurement plots (approximately 3000 plots in forests in Brazilian Amazonia), versus, for example, less than 90 plots for these forests in the study by Saatchi et al. (2007). For trees with diameter at breast height (1.3 m above the ground or above any buttresses) of 31.8 cm or larger, the estimates of wood volume in the boles have coefficients of variation (cv) of 0.18 in the forest type that accounts for 69% of the wood volume in the study area (dense lowland ombrophilous forest), and range from 0.18 to 0.24 for the five forest types that account for 99% of the wood volume, with a weighted average of 0.19 (based on 2077 plots in these forest types). For the Juma reserve itself the results are similar: dense lowland ombrophilous forest (cv = 0.18) represents 73% of the wood volume and the three forest types representing 99% of the volume have coefficients of variation ranging from 0.18 to 0.24 with a weighted average of 0.19 based on 1194 plots for these forest types. The multipliers for converting these wood volumes into total biomass, such as wood density, water content, the contribution of trees smaller than the minimum diameter in the surveys, adjustment for regional allometric differences from the equations used for the volume data reported in the RADAMBRASIL surveys, crown biomass, non-tree components, roots, dead biomass (necromass), palms, vines and other non-tree components all have substantial uncertainty. Our estimates have a number of features that assure lower uncertainty as compared to other estimates of Amazonian biomass. Our estimates include adjustments based on region-specific allometric equations and on region-specific wood density data associated with the volume of almost all tree species reported in the RADAMBRASIL surveys. We also have region-specific measurements of crown biomass as a function of bole biomass, as well as region-specific measurements of the water content of the wood (e.g., Nogueira et al., 2007, 2008a). Like other studies, we use literature sources for such components as roots and dead biomass (necromass), palms, vines and other non-tree components (Nogueira et al., 2008b: Table 1).

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Figure Legends

Fig. S1. Flowchart of the AGROECO model.

Fig. S2. Maps of land cover in the calibration stage (2003) and in the simulation of the scenarios considered in the study (2008).

Fig. S3. Result of the validation comparing the real and simulated maps for 2008.

Fig. S4. Baseline scenario simulated landscape in 2100: total study area (left panel) and Juma reserve (right panel).

Table S1

Area deforested and area of forest inside and outside of the Agrarian Forest Surface (AFS) used for calculation of the deforestation rate.

Area	Year	Deforestation	Forest	
		Area (ha)	Area (ha)	Average (ha)
Inside of the AFS (2-km buffer along roads)	2003	120,800	481,925	509,638
	2008	180,263	537,350	
Outside of the AFS (remaining forest excluding the AFS)	2003	65,088	8,768,125	8,706,150
	2008	75,363	8,644,175	

Table S2

Percentage of error between the number of cells in the simulated and real maps (PRODES for 2008).

Class	2008		% error
	Real map - PRODES (cells)	Simulated map (cells)	
Forest	1,473,485	1,471,491	0.14%
Deforestation	40,900	42,839	4.74%
Secondary vegetation	4,129	4,184	1.33%

Table S3
Area (km^2) of total forest, cumulative deforestation and secondary vegetation in the initial (2008) and final (2050) maps for the total study area in the three scenarios.

Study area (Class)	**PRODES**	**Baseline**	**Scenario with leakage (SL)**	**Scenario with reduced leakage (SRL)**
	2008 (km^2)	**2050 (km^2)**	**2050 (km^2)**	**2050 (km^2)**
Forest	92,092.8	77,397.8	77,445.6	77,874.3
Cumulative deforestation[†]	2,556.3	16,181.2	16,143.2	15,748.5
Secondary vegetation	258.1	1,328.2	1,318.4	1,284.3

[†] The cumulative deforestation does not include the mapped secondary vegetation. In the simulated maps, the “deforestation” class includes the areas cleared both by cutting of forest and by cutting of secondary vegetation.

Table S4

Area (km^2) of total forest, cumulative deforestation and secondary vegetation in the initial (2008) and final (2050) maps in the scenarios for the area of the Juma reserve.

Juma reserve (Class)	**PRODES**	**Baseline**	**Scenario with leakage (SL)**	**Scenario with reduced leakage (SRL)**
	2008 (km^2)	**2050 (km^2)**	**2050 (km^2)**	**2050 (km^2)**
Forest	5,573.9	4,521.5	5,179.0	5,179.5
Cumulative deforestation†	64.8	984.7	422.1	424.5
Secondary vegetation	2.3	134.8	39.9	37.0

† The cumulative deforestation does not include the mapped secondary vegetation. In the simulated maps, the "deforestation" class includes the areas cleared both by cutting of forest and by cutting of secondary vegetation.

Table S5

Analysis of the percentage of leakage simulated in the scenario with leakage (SL) and the scenario with reduced leakage (SRL).

Class (cells)†		**Scenarios – 2050 (cells)**				
		Baseline	**SL**	**SRL**	**100% Leakage (Baseline− SL)**	
Inside the Juma reserve	**Forest**	72,344	82,864	82,872	-10,520	
	Deforestation	15,755	6,753	6,792	9,002	
	Secondary veg.	2,157	639	592	1,518	
					Scenario with leakage (SL)	**Scenario with reduced leakage (SRL)**
Outside the Juma reserve	**Forest**	1,166,020	1,156,265	1,163,117	9,755 (92.7%)	2,903 (27.6%)
	Deforestation	243,144	251,538	245,184	8,394	2,040
	Secondary veg.	19,094	20,455	19,957	1,361	863

† The spatial resolution of a cell is 250 m (1 cell = 0.0625 km^2).

Figure S1

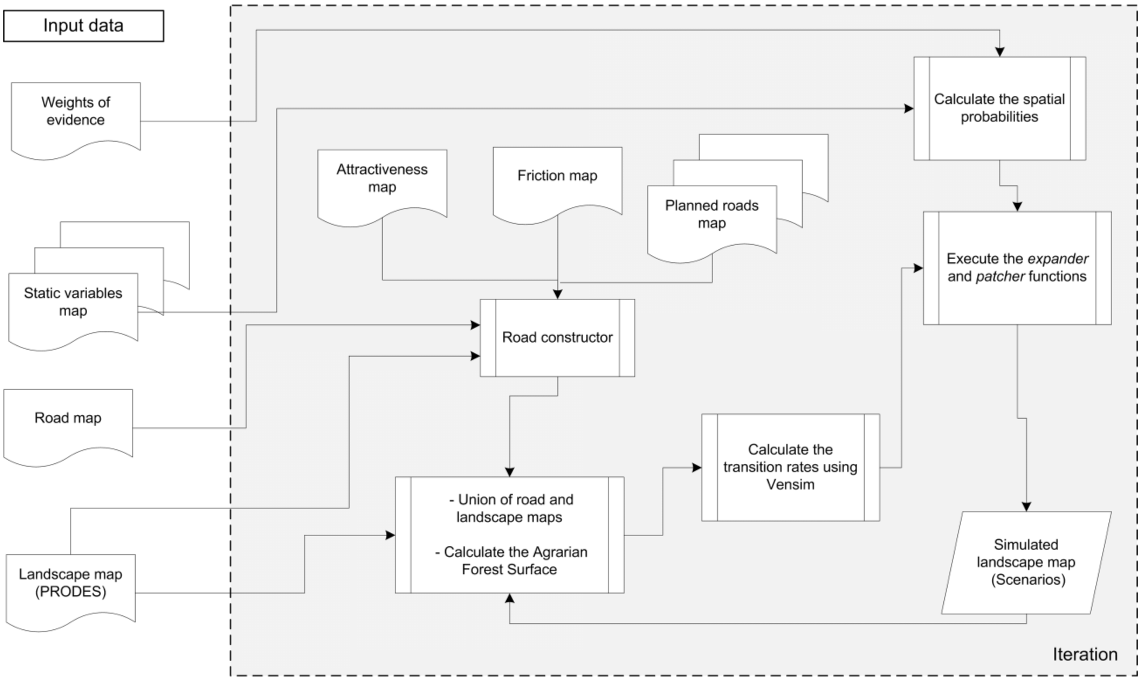

Input data
Weights of evidence
Static variables map
Road map
Landscape map (PRODES)
Attractiveness map
Friction map
Planned roads map
Road constructor
- Union of road and landscape maps
- Calculate the Agrarian Forest Surface
Calculate the transition rates using Vensim
Calculate the spatial probabilities
Execute the *expander* and *patcher* functions
Simulated landscape map (Scenarios)
Iteration

Figure S2

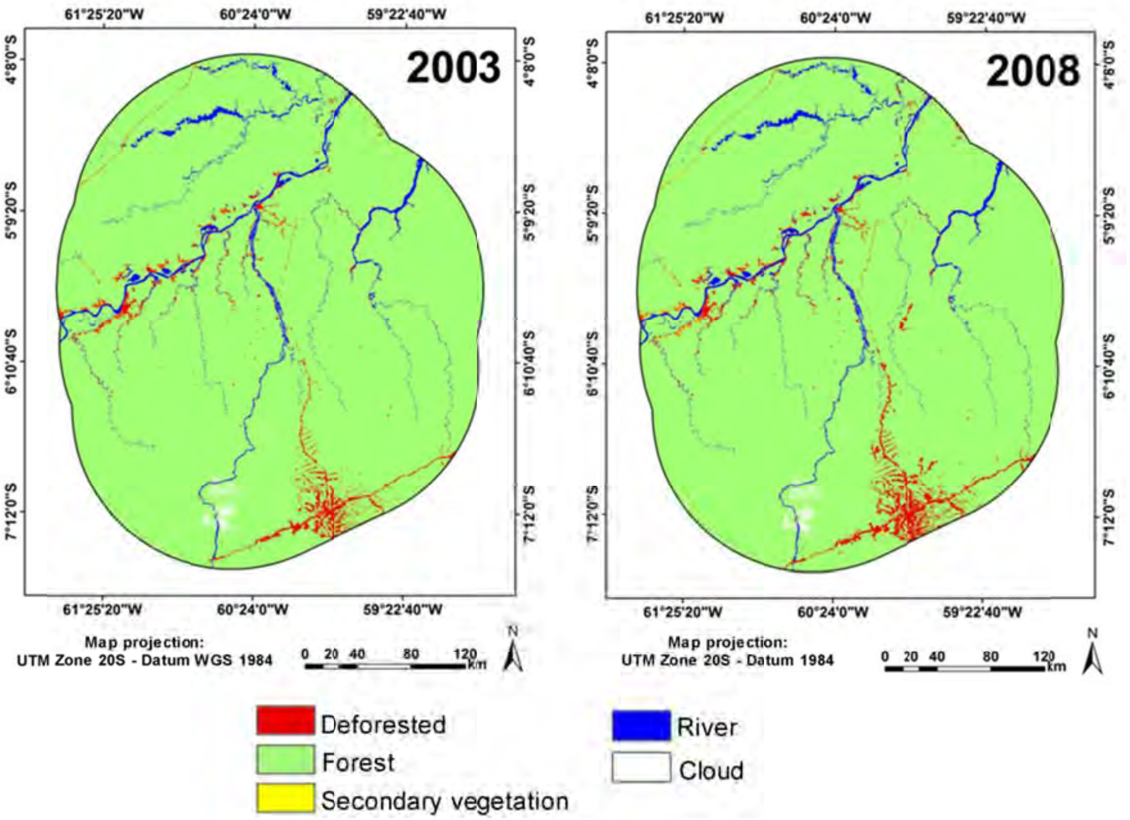

61°25'20"W
60°24'0"W
59°22'40"W
4°8'0"S
5°9'20"S
6°10'40"S
7°12'0"S
2003
Map projection:
UTM Zone 20S - Datum WGS 1984
0 20 40 80 120 km
N
61°25'20"W
60°24'0"W
59°22'40"W
4°8'0"S
5°9'20"S
6°10'40"S
7°12'0"S
2008
Map projection:
UTM Zone 20S - Datum 1984
0 20 40 80 120 km
N
Deforested
Forest
Secondary vegetation
River
Cloud

Figure S3

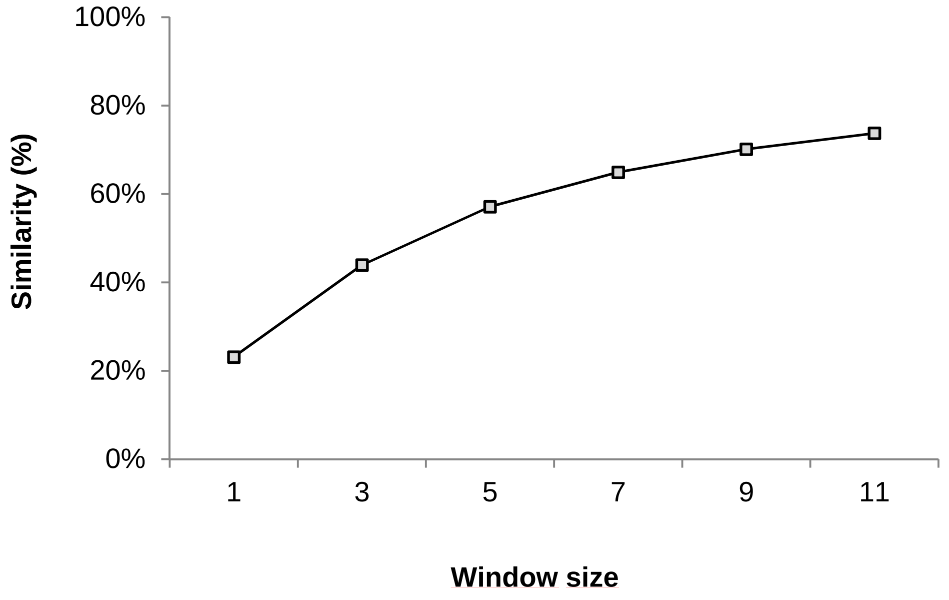
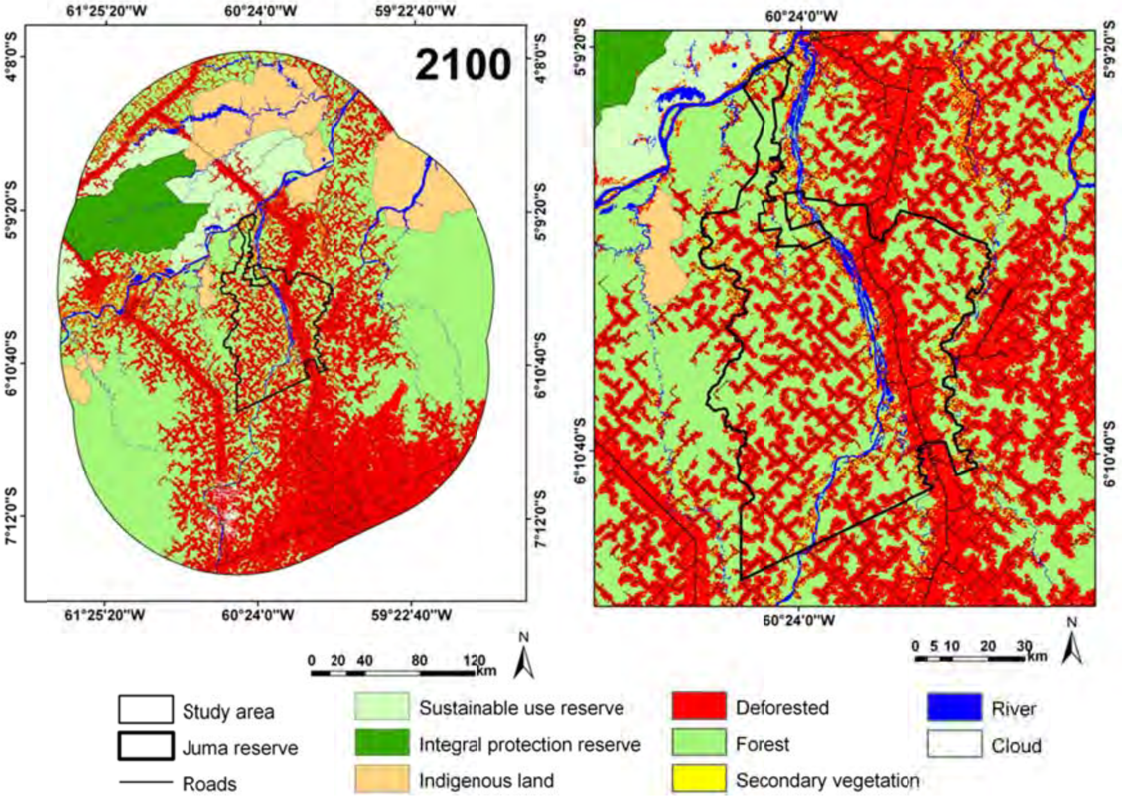


Figure S4


61°25'20"W
60°24'0"W
59°22'40"W
4°8'0"S
5°9'20"S
6°10'40"S
7°12'0"S
2100
0 20 40 80 120 km
N
Study area
Juma reserve
Roads
Sustainable use reserve
Integral protection reserve
Indigenous land
Deforested
Forest
Secondary vegetation
River
Cloud
0 5 10 20 30 km