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## **COMBINING SATELLITE REMOTE SENSING AND CENSUS DATA TO QUANTIFY AGRICULTURAL LAND USE CHANGE IN THE BRAZILIAN AMAZON**

*Combinação de Dados de Sensoriamento Remoto e Censos Agropecuários para a  
Quantificação da Mudança de Uso do Solo na Amazônia Brasileira*

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### **ABSTRACT**

As pasture and cropland have replaced forest cover in the Brazilian Amazon, the creation of spatial explicit time series of land use is an important concern in modeling land change. Despite much progress in mapping deforestation using satellite remotely sensed data, little is known about the distribution of agricultural land uses that replace forest cover in the Brazilian Amazon. In this paper we present a methodology to integrate satellite remote sensing and census data over 1996/1997 and 2006/2007 periods. Our resulting land use maps show the distribution and proportion of pasture as well as, temporary and permanent agriculture across the region. More than show an overall expansion of the total agricultural area between 1997 and 2007, our mapped land use time series aim to describe the effects of land use changes across the region over one decade.

**Keywords:** land use change, deforestation, Brazilian Amazon.

### **RESUMO**

Considerando que pastagens e plantações têm substituído a cobertura de floresta na Amazônia Brasileira, a criação de séries temporais espacialmente explícitas de usos agrícolas é uma preocupação importante na modelagem de mudanças da terra. Apesar dos avanços no monitoramento do desflorestamento pelo uso de dados de sensoriamento remoto, pouco se sabe ainda sobre a distribuição dos usos agrícolas que substituem a cobertura de floresta na Amazônia Brasileira. Neste artigo nós apresentamos uma metodologia para a integração dos dados de sensoriamento remoto e censos agropecuários nos períodos de 1996/1997 e 2006/2007. Nossos mapas resultantes mostram a distribuição e a proporção de pastagem, e de agriculturas temporárias e permanentes na região. Mais do que mostrar uma expansão da área agrícola total entre 1997 e 2007, nossas séries temporais de usos agrícolas objetivam descrever os efeitos dessas mudanças na região durante uma década.

**Palavras chave:** mudança de uso da terra, desflorestamento, Amazônia Brasileira.

## 1. INTRODUCTION

Investigating change in land cover and land use has been considered a key theme linked to deforestation in the Brazilian Amazon (Angelsen 1997; Machado 1998; Verburg, Kok et al. 2006). Data on forest loss have relied mostly on satellite remote sensing, measuring the extent of tropical deforestation. In the last three decades, the advent of remote sensing satellites has led to the development of instruments to systematically monitor land cover from space.

With 30m spatial resolution multispectral data, Landsat has become the workhorse of land cover change studies. These studies begin with data interpretation for the Brazilian Amazon, quantifying the location and amount of deforestation, which is a precursor of agricultural activity in many areas (Alves 2002; Cardille and Foley 2003; Lambin, Geist *et al.* 2006).

Few countries have projects to monitor change in forest cover that have been in place for several decades, most notably Brazil (Shimabukuro, Duarte *et al.* 2007; INPE 2010). INPE has four operating systems for monitoring deforestation in the Brazilian Amazon: PRODES, DETER, QUEIMADAS and DEGRAD. These systems aim to analyze the full land cover dynamics in the region.

Although the rates of forest loss have been examined across the Brazilian Amazon, little is known about the transition from mature forest to agricultural land uses. In this area, distribution, abundance and types of land use, distinctly from land cover, still need to be better understood.

The significant knowledge gaps related to the dynamics of human occupation across the region illustrate the need for a spatially explicit time series of agricultural land use data. Such time series could provide land change model inputs like land use history and condition of an area, while facilitating stronger projections of future scenarios (Cardille and Foley 2003; Aguiar 2006; Lambin, Geist *et al.* 2006; Alves, Morton *et al.* 2009).

Most information about agricultural land use in the Brazilian Amazon comes from agricultural census data (IBGE 1996; IBGE 2006). Agricultural censuses form the most complete survey of land management, including areas under different land use categories (pasture versus crops, for example), levels of mechanization and agricultural inputs, allow for detailed analyses of social, economic, and

environmental aspects of agriculture across the region (Cardille and Foley 2003; Alves, Morton *et al.* 2009).

Historically, agricultural areas in the Brazilian Amazon have increased by bringing more land into production. However, cropland expansion and agricultural intensification have varied across the region. Pará, for example, was characterized by the greatest expansion of pasture, increasing the area under production from 58,249 sq km in 1996 to 90,433 sq km in 2006 (IBGE 1996; IBGE 2006). On the other hand, in Mato Grosso, the area of temporary agriculture increased from 27,824 sq km in 1996 to 57,344 sq km in 2006, showing a high level of mechanization (IBGE 1996; IBGE 2006).

While it does not seem to be possible to create land use data using only satellite images, such information is crucial (Lambin, Geist *et al.* 2006). In this paper we present a methodology to combine satellite remote sensing and census data to quantify the distribution and fraction of major agricultural land uses – pasture, temporary and permanent agriculture – in the Brazilian Amazon. This work comparatively quantifies the distribution of the main land uses in 1996/1997 and 2006/2007 periods.

The paper is organized as follows. Section 2 presents a review of previous work. Section 3 presents the study area and spatial resolution. Section 4 presents the methodology used to combine satellite remote sensing and census data over 1996/1997 and 2006/2007 periods. Section 5 presents and discusses the resulting land use maps. We close the paper with final considerations regarding the land use dynamics in the Brazilian Amazon.

## 2. RELATED WORK

Methodological advances in providing spatial explicit time series of agricultural land use have captured the corresponding spatial detail needed for studies of land change and future landscape scenarios (Ramankutty and Foley 1999; Cardille and Foley 2003; Leite, Costa *et al.* 2010).

Ramankutty (1999), for example, presented an approach to derive geographically explicit changes in global croplands from 1700 to 1992. To reconstruct historical croplands, they basically used a remotely sensed land cover classification data set against cropland inventory data. From their 1992 cropland data within a land cover change model,

they reconstructed global 5 minute resolution data on permanent cropland areas from 1992 back to 1700.

Another example comes from Cardille and Foley(2003). They used census and satellite records to develop maps of the distribution and abundance of agricultural land uses across the Amazon in 1980 and 1995. In that work, the census-derived information in 1995/1996 was used to estimate agricultural activities in 1980, and from that time they generated a regression tree that statistically linked census and land cover classification data.

Finally, Leite and Costa *et al.*(2010) reconstructed and validated spatial explicit time series of land use in the Brazilian Amazon for the period 1940-1995, through a fusion of historical census data and contemporary land use classification. There, they fitted a linear regression model for land use change over time for each municipality, and the regression equation was used to replace any excluded data.

Although previous studies analyzed the reconstruction of historical agricultural land uses fusing remote sensing and census data, such reconstruction has not been carried out in Brazil since 2006 Agricultural Census was launched. In fact, no methodological approach was presented in a way which could be easily updated.

### 3. STUDY AREA AND SPATIAL RESOLUTION

The study area is the Brazilian Amazon rainforest, which covers an area of more than 5 million sq km. In our database, all attributes representing deforestation and land uses – pasture, temporary and permanent agriculture – were aggregated to grid cells of 25 km x 25 km, counting a total of 8580 cells (Figure 1).

Our grid cells were created into the *TerraView* application, meaning that the resulting database respected the GIS library *TerraLib* standards (TerraView 2010).

### 4. COMBINING SATELLITE REMOTE SENSING AND CENSUS DATA

In this section we summarize the methodology used to combine satellite remote sensing and census data over 1996/1997 and 2006/2007 periods. Our methodology was processed using *aRT*, an *R* package that provides an integration between the

statistical software *R* and *TerraLib*(Andrade, Ribeiro *et al.* 2005).

The *aRT* package was useful to easily integrate our *TerraLib* database (“*db\_25k*”) to the statistical functionalities available in *R*. In addition, *R* environment allows a good reproduction of the presented results by use of scripts.

#### 4.1 Deforestation Maps

##### 4.1.1 Prodes Methodology

We started from the Landsat TM-based deforestation maps produced under the Amazon-monitoring program (PRODES) of INPE (INPE 2010). The first digital version of these deforestation maps was created in 1997, and since 2000 they have been produced annually. PRODES uses an automatic procedure to analyze TM images based on techniques of *linear spectral mixture model*, *image segmentation* and *classification by regions*(Valeriano, Mello *et al.* 2004).

To estimate the extension of deforested areas for 1997 TM images, a shade fraction image was used by INPE, which enhances the difference between forest and deforested areas. To estimate the increment of deforested areas from 2000, soil fraction images were used, mainly because they enhance the difference between forest and recent clear cut areas(Valeriano, Mello *et al.* 2004; INPE 2010).

##### 4.1.2 Our Methodology

From PRODES 2008 deforestation map, we selected the PRODES class labels needed to create the cumulated deforestation (extension of deforestation) maps for 1997 and 2007. All classes of deforestation occurring until 1997 and 2007 were computed, respectively (Appendix A). Figure 2 presents the deforestation map with its classes covered by our grid of cells.

Appendix B shows how we computed the proportion of cumulated deforestation for each cell of our grid of 25km x 25km in 1997 and 2007. We present the *aRT* script used to compute the values into each cell. Beginning with the DBMS connection to the MySQL database (“*db\_25k*”), we selected our layers of deforestation map (“*PRODES\_1997\_2008*”) and cells (“*AMZ\_CELULAR\_25000*”). Afterwards, we selected the labeled pixels inside each cell.

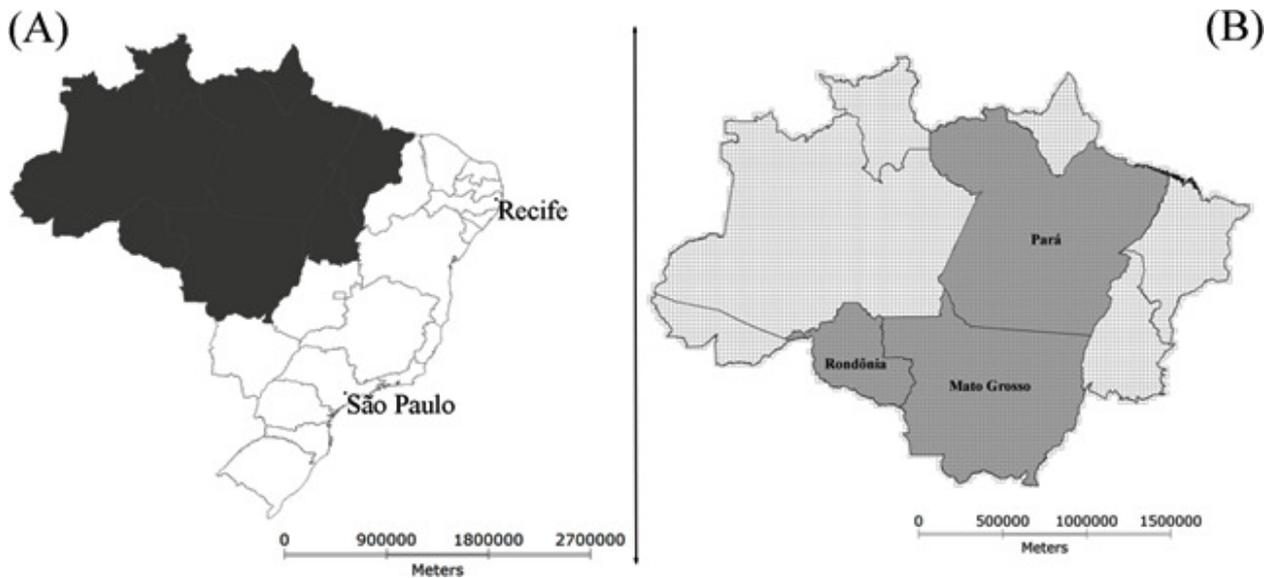


Fig. 1 – (A) Map of Brazil showing the location of the Brazilian Amazon region (all in darker gray), and the location of São Paulo and Recife cities. (B) Regular grid of 25 km x 25 km over the Brazilian Amazon region; the states of Pará, Rondônia and Mato Grosso are shown in gray.

The proportion of each class label was defined based on the PRODES methodology, meaning that the class labels were quantified considering the cloud cover over time. For example, polygons in the PRODES 2008 deforestation map labeled with “D1997\_0” represent deforested areas detected in 1997 (“D1997”), counting 0 years of previous cloud cover over these polygons (“\_0”). In the same way, polygons labeled with “D2000\_3” represent deforested areas detected in 2000 (“D2000”), counting 3 years of previous cloud cover over these polygons (“\_3”), and so on and so forth. For 1997, we show Equation 1 as one example:

$$\begin{aligned}
 acumul1997 = & (length(which(pixels==42)) \\
 & + 0.25 * length(which(pixels==45)) \\
 & + 0.2 * length(which(pixels==48)) \\
 & + 0.17 * length(which(pixels==5)) \\
 & + 0.14 * length(which(pixels==10)) \\
 & + 0.13 * length(which(pixels==16)) \\
 & + 0.11 * length(which(pixels==23)))
 \end{aligned}
 \tag{1}$$

Finally, we divided the number of labeled pixels by the total number of pixels inside the cell, and wrote the results into the database (“ACUM\_1997”).

## 4.2 Land Use Maps

The cumulated deforestation in 1997 and 2007 was decomposed into the following main agricultural uses – pasture, temporary and permanent agriculture – combining the PRODES deforestation map in 1997 and 2007 and census information from municipality-based Agricultural Census in 1996 and 2006, respectively (IBGE 1996; IBGE 2006).

Census data were converted from polygon-based information to grid cells of 25 km x 25 km. The location of agricultural areas for each municipality was taken from the deforestation map (computed previously – Section 4.1.2). On the other hand, the proportion of each agricultural use within each cell was taken from the census data (Appendix C).

The proportion of each agricultural use was computed for each municipality considering the total area of each land use (pasture, for example) divided by the area of this municipality. In our methodology we assumed that the proportion of land use types was uniformly distributed over the deforested areas of each municipality (Aguiar 2006; Aguiar, Câmara et al. 2007).

In Appendix C, we present the *aRT* script used, and the description of the steps are similar to the ones described in section 4.1.2. The difference here is that we also selected the layer related to census data (“*CENSO\_1996\_625*”), which gives us the proportion of each agricultural use for each municipality.

In that *aRT* script, we first selected the intersections between each cell with each municipality (*getClip*). For each intersection, we computed the number of total labeled pixels multiplied by the proportion of the land use (pasture, in this example). This result is computed for each intersection inside one cell, and then added and multiplied by the resolution of the pixel (100m), and divided by the area of the cell (25km x 25km).

## 5. RESULTS AND DISCUSSION

This section summarizes the main findings and compares the results obtained by land use time series in 1996/1997 and 2006/2007 periods. Table 1 shows the trends in the four land uses across the Brazilian Amazon, expressed as number of grid cells in which the proportion under the given land use is more than 10%. Additional results are shown by Espindola and Aguiaret al.(2012).

Figure 3 shows that deforestation increased over these 10 years (1997-2007), and also that it tends to occur close to previously deforested areas, showing a strong spatial structure, as pointed out by other authors(Alves, Morton *et al.* 2009). Figure 4 shows that pasture spread over the whole deforested areas, being the major land use in both periods (1997 and 2007), and has increased following the deforestation patterns. Pasture was also established mainly across eastern Pará, central Rondônia, and north of MatoGrosso.

For temporary agriculture, as shown in Figure 5, two states deserve attention. In Maranhão, temporary agriculture moved from the center to the north of the state. In MatoGrosso, the area increased more than 100% from 1996 to 2006 (IBGE 1996; IBGE 2006). The forest conversion to cropland in MatoGrosso represents a case of particular interest due to massive investments made by commercial soybean farmers, as well as to the success of farming systems and crop breeding research. On the other hand, permanent agriculture is the smallest agricultural land use category in the study area. Over ten years, it was replaced by pasture in Rondônia, but increased in some areas of the northeast of Pará, as shown in Figure 6.

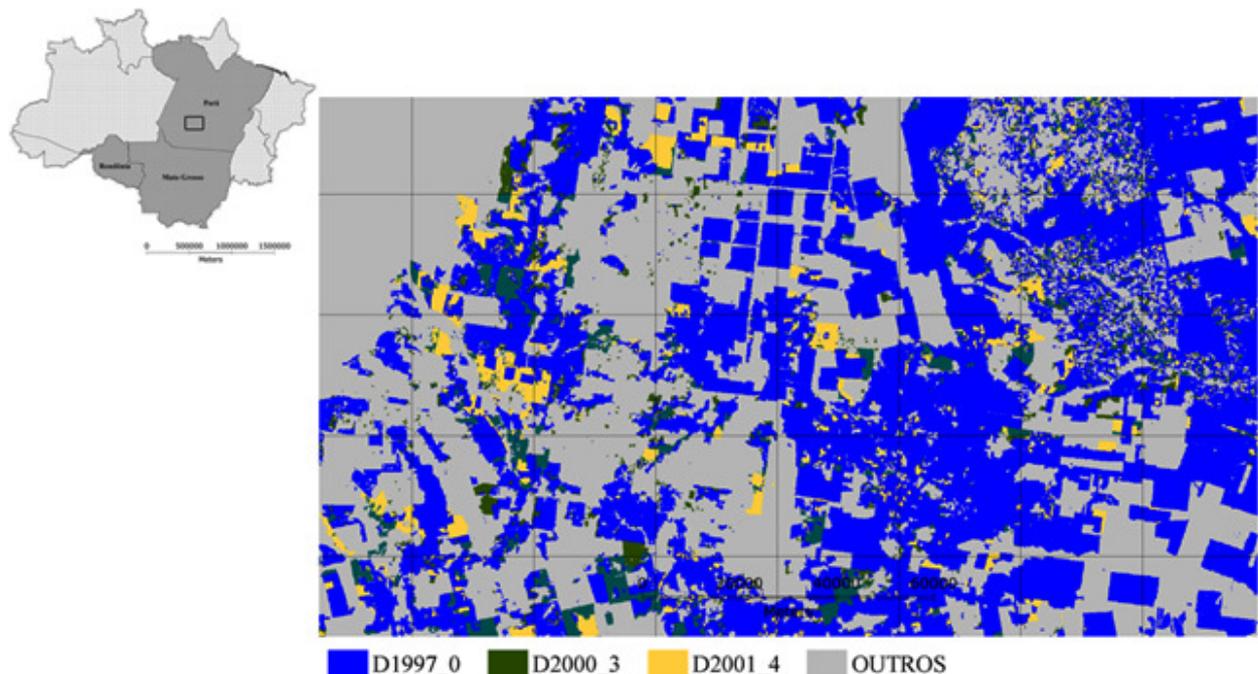


Fig.2 – Regular grid of 25 km x 25 km over PRODESdeforestation map.

Table 1 – Land use trends in the four land uses across the Brazilian Amazon: numbers express the cells under the given land use is more than 10%.

Quantitative Land Use Trends		
	1996/1997	2006/2007
Number of valid cells	8580	8580
Number of cells with more than 10% deforestation	1723	2293
Number of cells with more than 10% pasture	1341	1936
Number of cells with more than 10% temporary agriculture	219	396
Number of cells with more than 10% permanent agriculture	14	92

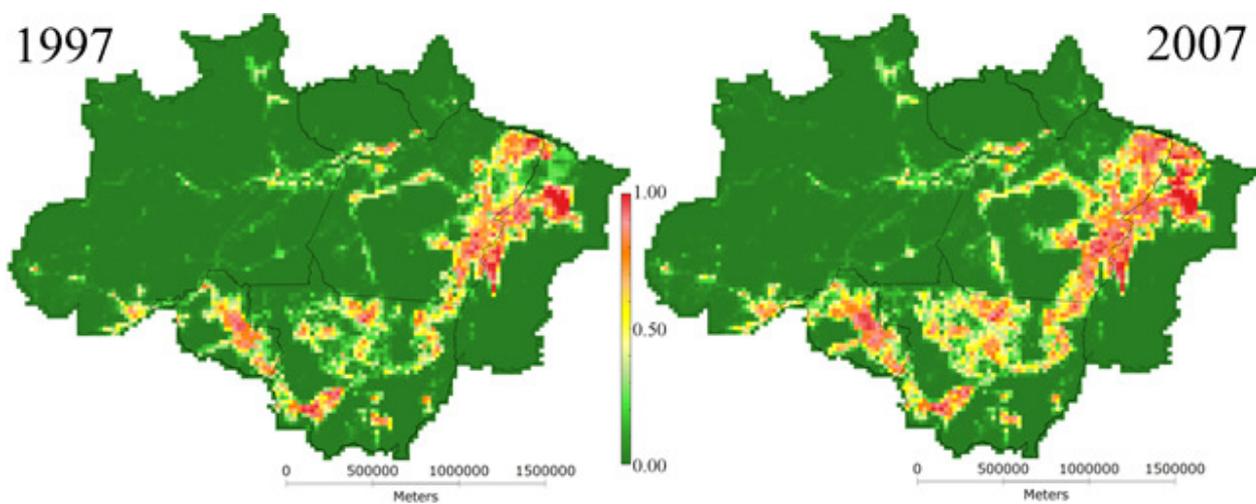


Fig. 3 – Proportion of cumulative deforestation for each cell in 1997 (left) and 2007 (right).

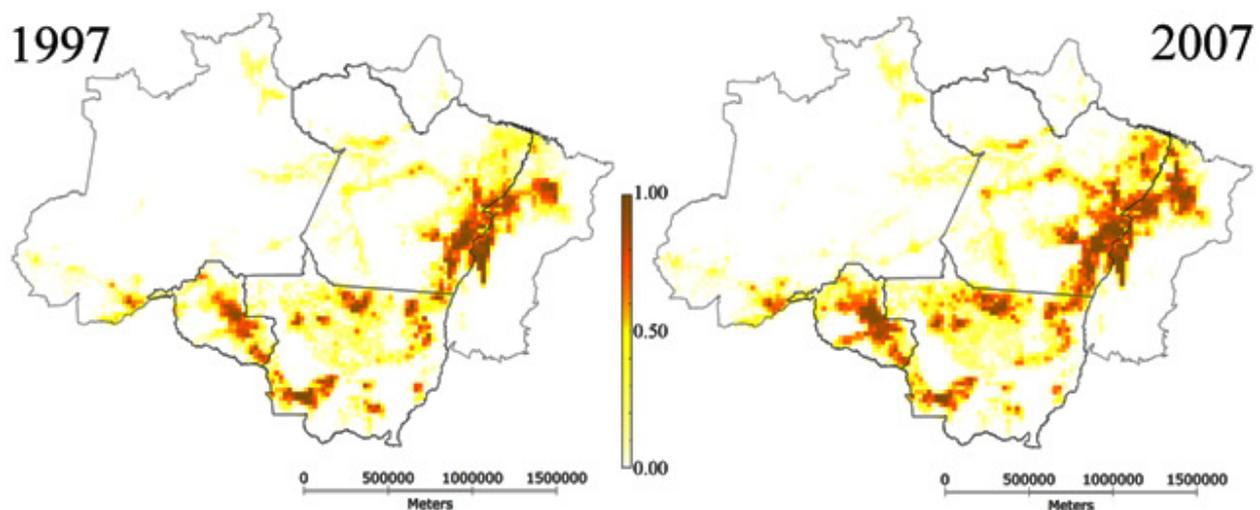


Fig.4 – Proportion of pasture in 1997/1996 (left) and 2007/2006 (right).

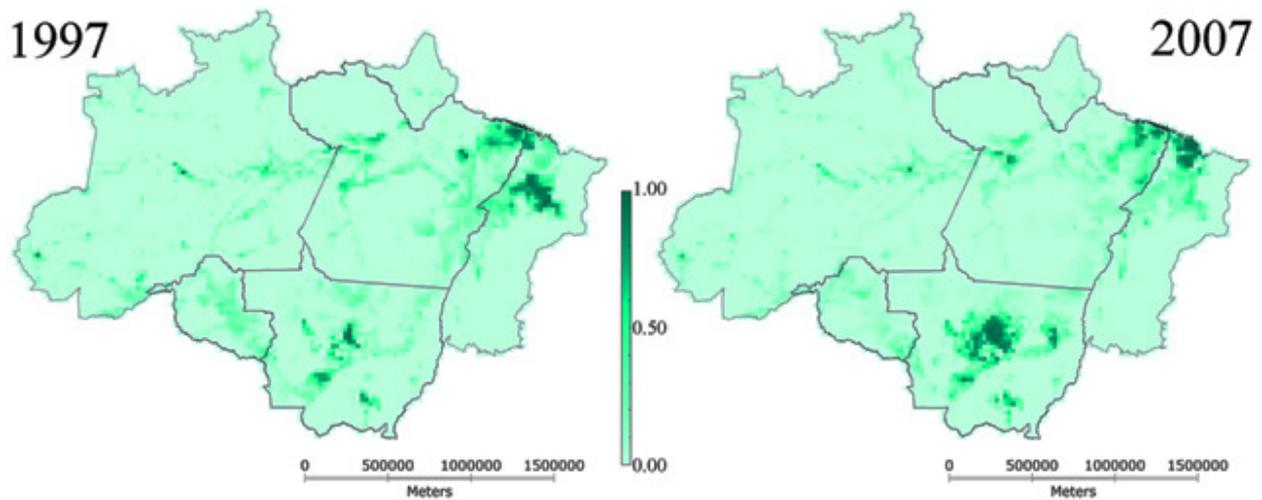


Fig.5 – Proportion of temporary agriculture in 1997/1996 (left) and 2007/2006 (right).

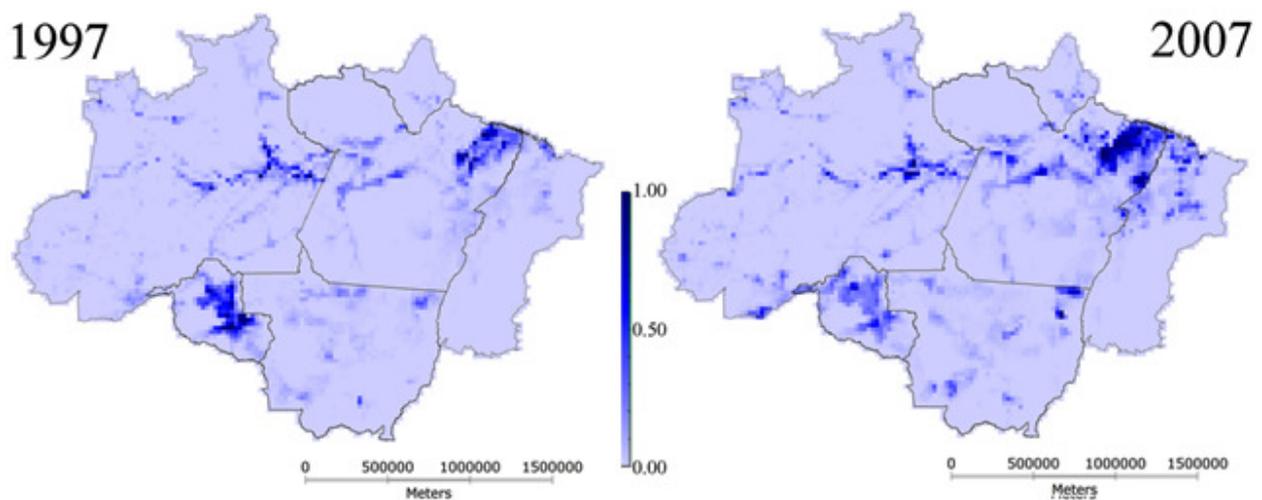


Fig.6 – Proportion of permanent agriculture for 1997/1996 (left) and 2007/2006 (right).

In both periods, overall agricultural activities were concentrated in the southeast region of the study area, especially across eastern Pará, central Rondônia, and north of MatoGrosso. From these areas and isolated patches, agricultural activity rapidly spread over 1996/1997 and 2006/2007 periods.

## 6. CONCLUSIONS

Information from agriculture censuses can be integrated with satellite remote sensing data to provide additional information that would otherwise not be available. This combination allows analysis of the spatially explicit patterns of deforestation and agricultural uses within the Brazilian Amazon.

Since deforestation precedes the establishment of much of the new agriculture in the Brazilian Amazon, in this paper we estimated the distribution and the proportion of pasture as well as, temporary and permanent agriculture across the region. The mapped land use time series aim to explain the effects of land use changes across the region over one decade.

The results shown here require further validation in order to verify the quantification of those land use changes. Suggestion for future research is the use of data samples collected in the field to compute statistical analyzes of the results. However, our maps may be used in land change models, which are capable of simulating the major socioeconomic and biophysical driving forces of land use and cover change.

## APPENDIX A

PRODES classes:

Label	Class	Accumulated Deforestation in 1997	Accumulated Deforestation in 2007
1	OUTROS	no	no
2	D2002_0	no	YES
3	D2002_1	no	YES
4	D2002_4	no	YES
5	D2002_5	YES	YES
6	D2003_0	no	YES
7	D2003_1	no	YES
8	D2003_2	no	YES
9	D2003_5	no	YES
10	D2003_6	YES	YES
11	D2004_0	no	YES
12	D2004_1	no	YES
13	D2004_2	no	YES
14	D2004_3	no	YES
15	D2004_6	no	YES
16	D2004_7	YES	YES
17	D2005_0	no	YES
18	D2005_1	no	YES
19	D2005_2	no	YES
20	D2005_3	no	YES
21	D2005_4	no	YES
22	D2005_7	no	YES
23	D2005_8	YES	YES
24	D2006_0	no	YES
25	D2006_1	no	YES
26	D2006_2	no	YES
27	D2006_3	no	YES
28	D2006_4	no	YES
29	D2006_5	no	YES
30	D2006_6	no	YES
31	D2006_OUT	no	YES
32	D2007_0	no	YES
33	D2007_1	no	YES
34	D2007_2	no	YES
35	D2007_3	no	YES
36	D2007_4	no	YES
37	D2007_5	no	YES
38	D2007_6	no	YES
39	D2007_7	no	YES
40	D2007_OUT	no	YES
41	D2008_0	no	no
42	D1997_0	YES	YES
43	D2000_0	no	YES
44	D2000_2	no	YES
45	D2000_3	YES	YES
46	D2001_0	no	YES
47	D2001_3	no	YES
48	D2001_4	YES	YES

## APPENDIX B

*aRT* script used to compute the proportion of cumulated deforestation for each cell in 1997.

```
require(aRT)
conn=openConn("root", "", 3306)
db=openDb(conn, "db_25k")
showLayers(db)

#CELLS
lcells=openLayer(db,
"AMZ_CELULAR_25000")
tcells=openTable(lcells)

#PRODES
lraSTER=openLayer(db,
"PRODES_1997_2008")
raster=getRaster(lraSTER, as.sp=FALSE)

#OPERATOR
q=openQuerier(lcells, geom="cells")
quant=summary(q)$elements
print(quant)
result=vector("numeric", quant)
ids=vector("character", quant)

for(i in 1:quant)
{
next_cell=getData(q, quantity=1)
nc=as.aRTgeometry(next_cell)
pixels=getPixels(raster,
as.aRTgeometry(next_cell))
total=length(pixels)

acumul1997=(length(which(pixels==
42))+0.25*length(which(pixels==45))
+0.2*length(which(pixels==48))+0.17*length
(which(pixels==5))+0.14*length(which(pixe
ls==10))+0.13*length(which(pixels==16))
+0.11*length(which(pixels==23)))

porc=acumul1997/total
print(i)
result[i]=porc
ids[i]=getID(next_cell)
}

df=data.frame(object_id=ids,
ACUM_1997=result, stringsAsFactors=FALSE)
createColumn(tcells, "ACUM_1997",
type="n")
```

```
updateColumns(tcells, df)
```

## APPENDIX C

*aRT* script used to compute the proportion of pasture for each cell in 1997.

```
require(aRT)
conn=openConn("root", "", 3306)
db=openDb(conn, "db_25k")
showLayers(db)

#CENSUS
lcenso=openLayer(db,
"CENSO_1996_625")
censo_pols=getPolygons(lcenso,
as.sp=FALSE)
censo_table=openTable(lcenso)
censo_data=getData(censo_table)
colnames(censo_data)

#PRODES
lprodes=openLayer(db,
"PRODES_1997_2008")
prodes_raster=getRaster(lprodes,
as.sp=FALSE)
resol_raster=(100/1000)*(100/1000)
print(resol_raster)

#CELLS
lcells=openLayer(db,
"AMZ_CELULAR_25000")
tcells=openTable(lcells)
resol_cells=(25)*(25)
print(resol_cells)
const=(resol_raster)/(resol_cells)
print(const)

#OPERATOR
q=openQuerier(lcells, geom="cells")
quant=summary(q)$elements
print(quant)
result=vector("numeric", quant)
ids=vector("character", quant)

for(i in 1:quant)
{
next_cell=getData(q, quantity=1)
nc=as.aRTgeometry(next_cell)
pols=getClip(censo_pols, nc)
print(i)
```

```

if(is.null(pols))
{
result[i] = 0.0
}
else
{
result[i]=sum(sapply(getID(pols), function(id)
{
ss=subset(pols, getID(pols)==id)
pixels=getPixels(prodes_raster,
as.aRTgeometry(ss))
const*(length(which(pixels==42))+0.25*length(wh
ich(pixels==45))+0.2*length(which(pixels==48))
+0.17*length(which(pixels==5))+0.14*length(
which(pixels==10))+0.13*length(which(pixels==16))
+0.11*length(which(pixels==23)))*(cens
o_data[which(censo_data[,44]==id),38])
}))
}
ids[i] = getID(next_cell)
}

df=data.frame(object_id_=ids,
CENSO96_PASTAGEM=result,
stringsAsFactors=FALSE)
createColumn(tcells,
"CENSO96_PASTAGEM", type="n")
updateColumns(tccells, df)

```

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