Mapping the agricultural frontier in Mato Grosso with remote sensing data

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Abstract. An active agricultural frontier is moving forward in the Brazilian Amazon area, especially in the State of Mato Grosso where crop expansion has been considered as a main driver of deforestation for more than 30 years. Geographical concepts of the agricultural frontier assume that its progress is carried out through five stages (pre-settlement, occupation, consolidation, intensification and intensive stages), corresponding to the evolution of three frontiers (deforestation, economic and intensification frontiers). This paper aims at proposing a remote sensing-based methodology to map the spatio-temporal evolution of these frontiers and the evolution stages of the agricultural frontier in Mato Grosso. The method is based on the definition of an agrarian locality scale and on land-use based indices. The quality of the method is then dependent on the accuracy of the input data used. Here deforestation (provided by INPE and SEMA-MT) and classification maps (computed on MODIS EVI time series) are used. The results allow to visualize the evolution of three important phenomena in Mato Grosso during the 2000-2006 period: increase in deforestation, crop expansion and agricultural intensification. Final maps highlight the fact that few areas have reached the final intensive stage of the agricultural frontier, reminding that Mato Grosso is still experiencing a very active colonization process.

Palavras-chave: agricultural frontier, deforestation, crop expansion, agricultural intensification, MODIS, Mato Grosso

1. Introduction

For more than 50 years, the successive Brazilian governments have initiated a development and integration process of the Brazilian area of the Amazonian basin to the national territory. Such decisions have induced radical transformations of the Amazonian landscapes and societies. The arrival of inumerous migrants in wild areas allowed an undeniable economic development but the environmental and social consequences are, at least, worrying. The State of Mato Grosso (fig. 1), located in the Southern part of the Amazonian basin, illustrates perfectly such an evolution. Since the 1970's, the economic development has been sustained by a rapid agricultural growth (especially based on pastures and soybean expansion) imported by migrants coming from the southern states of Brazil.

Nowadays, the positive and negative consequences of such a colonization program can be estimated and criticized. The agricultural growth carried high incomes for the state and its farmers. But this progress did not benefit to the entire population (little farmers and indigenous people were excluded), so that social inequalities increased. Environmentally, ecosystem services were affected since crop expansion was designated as a major driver of deforestation in Mato Grosso (Morton et al., 2006). Moreover, the new intensive agricultural practices applied by the farmers (based on the application of pesticides and fertilizers and the adoption of double cropping systems) imply soil and water pollution issues.

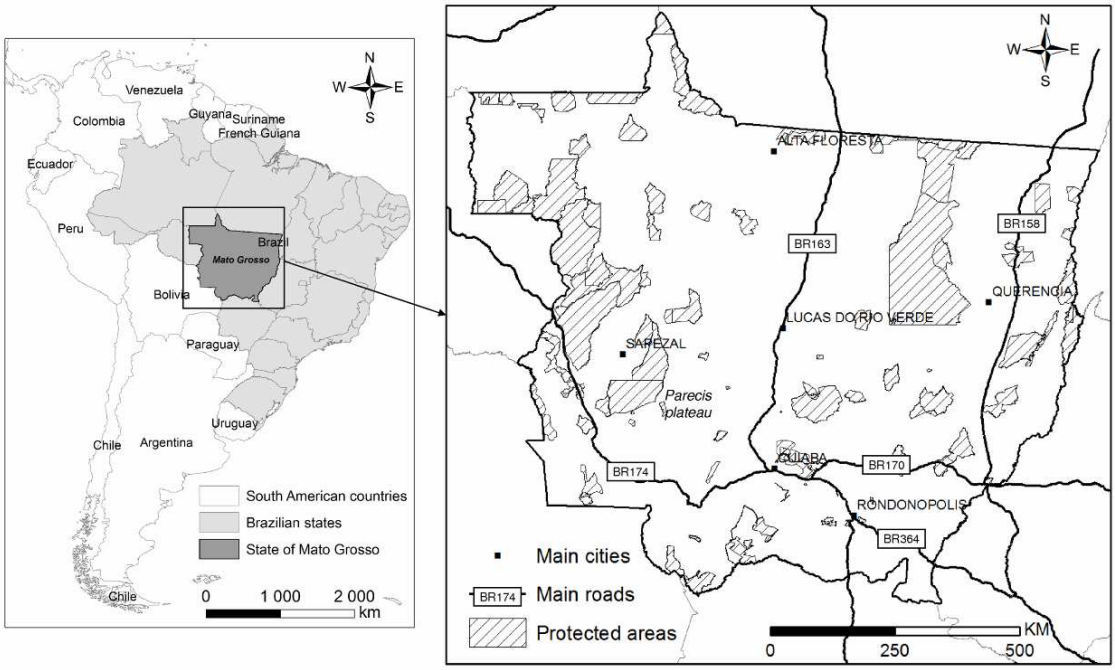

Figure 1. Location and presentation of the state of Mato Grosso.

Actually, the territorial evolution here introduced illustrates the progress of an active pioneer frontier, which can be defined as a rural area in contact with virgin areas, implying some transformations of the natural space (Droulers et Le Tourneau, 2000). The agricultural activity usually represents the driving force of the pioneer frontier, so that it sometimes correspond to an agricultural frontier. This agricultural frontier progresses through five stages (pre-settlement, occupation, consolidation, intensification and intensive stages) transforming a territory from a wildland to an agriculturally intensive territory (DeFries et al., 2004). These stages are characterized by different land-use types and the land-use transitions from one type to another correspond to three successive frontiers (figure 2):

- The **deforestation frontier** marks the land-use transition from a *pre-settlement* to an *occupation* stage. It is linked to the arrival of migrants who need to clear some areas in order to begin an agricultural activity. In that case, the amount of deforestation is correlated to the number of new migrants.

- The **economic frontier** marks the land-use transition from an *occupation* stage to a *consolidation* stage. It is linked to the transition from a subsistence to a capitalist agriculture. Thus, its evolution depends on the profitability of the agricultural commodities produced, i.e. on the price of commodities as defined by the international rate exchanges in the context of soybean crops.

- The **intensification frontier** marks the land-use transition from a *consolidation* to an *intensification* stage, leading to the ultimate *intensive* stage. It appears when new areas to expand crops become rare and expensive. The only way to improve the production then consists in adopting new agricultural practices. In Mato Grosso, this intensification process is

done through the application of double cropping systems, the soybean harvest being quickly followed by a corn or cotton harvest.

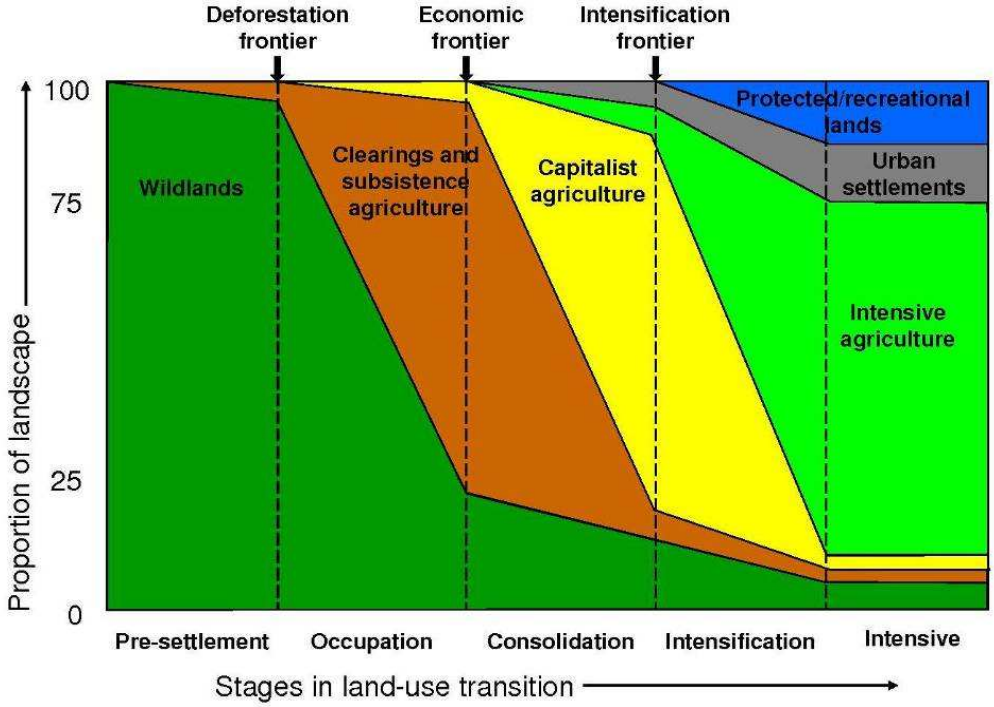

Figure 2. Stages of the evolution of the agricultural frontier and the corresponding land-use types (adapted from DeFries et al., 2004).

As the evolution of the agricultural frontier can be characterized by a succession of land-use transitions (DeFries et al., 2004), relevant remote sensing techniques can be used to map frontiers. Indeed, remote sensing data have proven to be efficient for mapping deforestation, crops and agricultural practices. For instance, the PRODES and DETER projects lead by INPE (National Institute for Space Research) are two successful initiatives implemented to map deforestation in Brazilian Amazonia. Relevant examples of crop mappping based on MODIS data include soybean and corn mapping in the US Great Plains (Wardlow and Egbert, 2008) or even in Mato Grosso (Morton et al., 2006). Finally, agricultural practices such as double cropping systems were accurately detected by MODIS imagery in Mato Grosso by Galford et al. (2008). Most classifications techniques based on MODIS data are based on time series of vegetation indices (either NDVI or EVI) that allow analyzing the phenological cycles of the vegetation cover.

Based on the concepts of the agricultural frontier stated above and the potentialities of remote sensing techniques at moderate spatial resolution (MODIS sensor), the objective of this paper is to propose a satellite-based method to 1) monitor the evolution of the deforestation, economic and intensification frontiers and 2) map the evolution stages of the agricultural frontier in Mato Grosso.

2. Data and methods

1.1 Data

Two datasets were used to carry out this study. First, deforestation maps provided by INPE and SEMA-MT (State Secretary of Environment of Mato Grosso) were acquired. These data are annual deforestation maps for the 2000-2006 period. The INPE data presents the advantage to be automatically and annually produced based on landsat data as part of the PRODES project. However, these data only consider deforestation in the forest biome, which only stands in the northern half of Mato Grosso State. Complementary, the deforestation maps

provided by SEMA-MT take the entire State into consideration, including the cerrado (Brazilian savanna) and the Pantanal biomes. However, these maps are manually produced based on CBERS and Landsat data on a nearly annual basis. Thus, to take advantage of both datasets, we compared them and fused it after rasterization at MODIS resolution by considering as deforested every pixel that was detected as deforested by at least one dataset. Even if the deforestation maps were produced for each year between 2000 and 2006, only the 2000 and 2006 deforestation maps were used in this study.

Second, MODIS TERRA/EVI data (MOD13Q1 product) at a 250 m spatial resolution and 16 days temporal resolution were acquired from July 2000 to August 2007. The MODIS EVI annual time series (from July to July) where then classified through a supervised classification based on data collected during a field campaign. The mapping process is based on two successive classifications to separate: 1) cropped areas from other vegetation covers (forest, cerrado and pasture) and 2) agricultural practices (single versus double cropped areas). The entire classification methodology is detailed in Arvor et al. (in press). The classification accuracy for discriminating crops from other biomes was good (Overall accuracy = 85.50%, Kappa index = 0.8067 and user's and producer's accuracies >95%). Also, the classification method to separate single and double cropping systems was satisfying (Overall accuracy = 90.5% and Kappa index = 0.81). Two classifications maps for the 2000-2001 and 2000-2006 harvests were used in this study.

1.2 Method

The method was divided in two steps. First, we used the input data to map the deforestation, economic and intensification frontiers. This implies: 1) to define a relevant spatial scale for observing the frontiers' evolution, and 2) to compute indices to represent them. For Albaladejo et al. (1996), it exist three spatial scales for studying rural areas: the farm scale, the agrarian locality and the state or county. The farm scale was considered as too fine to observe land use dynamics on the entire state of Mato Grosso. The state or county scale does not allow to map the intra-state spatial variability of frontiers. Thus, we defined an intermediate scale corresponding to an agrarian locality. According to the SEMA-MT, 1175 agrarian localities were reported in Mato Grosso. Thus, when dividing the total State area (906000 km²) by the number of agrarian localities, we estimated that the mean area for such a locality is 771 km². Then, we divided the state of Mato Grosso in a regular grid of 0.25°x0.25° cells corresponding to an area of nearly 770 km².

Based on this grid and our input maps, we computed, for each cell, three indices corresponding to the three studied frontiers. The deforestation frontier is mapped by computing the percentage of deforestation per cell. The economic frontier is mapped by computing the percentage of cropped areas as compared to the total deforested area per cell. The intensification frontier is mapped by computing the percentage of areas cultivated with double cropping systems as compared to the total cropped area per cell. Finally, these three maps are resampled with a Spline algorithm in order to improve the visualization of the spatial and temporal evolution of the frontiers.

Second, these output maps are crossed to map the evolution stage of the soybean territories in Mato Grosso. The method to define a stage is adapted from DeFries et al. (2004) and Clairay (2003) and is summarized in figure 3.

Eight classes of land use transitions were identified and defined as follows:

- ***pre-settlement (class 1)***: wildlands are dominant in the study area, i.e. non-deforested area represent more than 90%.
- ***occupation***: wildlands are being cleared but are still majority in the study area, i.e. non-deforested areas represent between 50 and 90%. Thus, deforestation is evolving but it is necessary to indicate if these clearings are due to agricultural expansion ot not. Thus, we

differentiated ***agricultural occupation (3)*** (inside the deforested area, crop area > non-cropped area). On the contrary, if cropped areas are less than non-cropped areas. We call it ***non-agricultural occupation (2)***.

- ***consolidation***: wildlands represent between 25% and 50% of the study area. We then distinguished between ***non-agricultural consolidation (4)*** stage (when cropped areas are less than non-cropped areas) and ***agricultural consolidation (5)*** stage.
- ***intensification***: wildlands stand for less than 25% of the study area. If the cropped area is higher than the non-cropped area, we considered it as an ***agricultural intensification (7)*** stage, otherwise we called it ***intensification on non-agricultural areas (6)*** stage.
- ***intensive (8)***: the final intensive stage is achieved when wildlands nearly disappeared (less than 25% of the study area), crops represent more than 50% of the deforested areas and double cropping systems stand for more than 50% of the cropped areas.

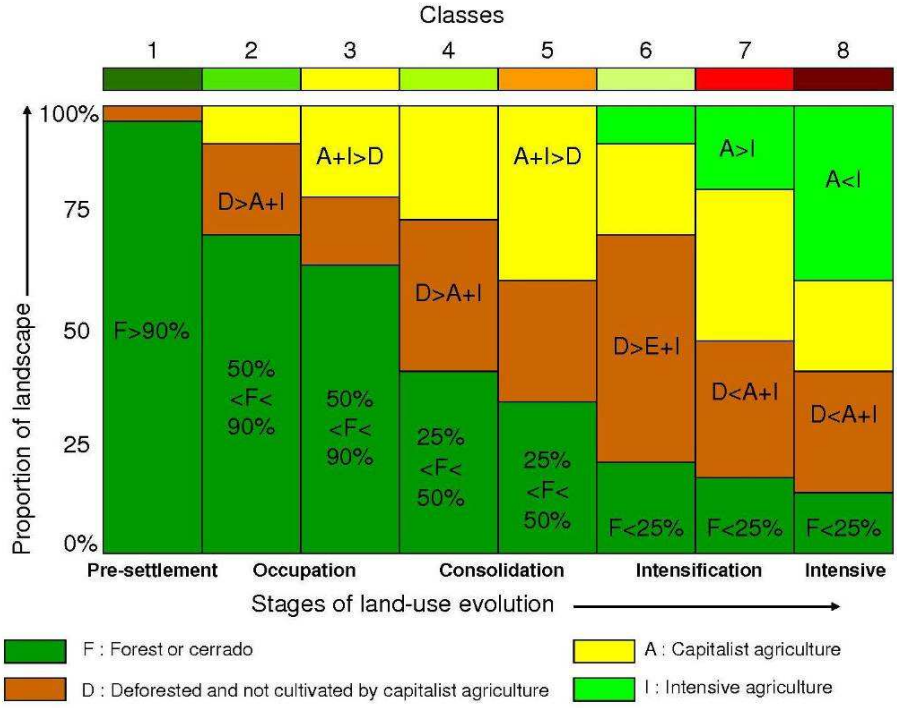

Figure 3. Thresholds applied to assign classes to stages of land-use evolution.

3. Results

The figure 4 indicates that the deforestation frontier evolved up north between 2000 and 2006. Indeed, while the most deforested areas are still located in the southern part of Mato Grosso (i.e. the cerrado biome), it appears that deforestation increased drastically in the central, northern and western areas of Mato Grosso, i.e. in the rainforest biome. Actually, these two maps highlight the importance of the federal politics in the deforestation process since 1) the most deforested areas are located along the main roads planned by the federal governments, and 2) the less deforested areas are located in the protected areas (indigenous lands and environmental conservation units) also organized by the federal governments.

The figure 5 represents the evolution of the economic frontier, corresponding to the agricultural expansion. In 2000-2001, the agricultural production was concentrated in three main agricultural areas: the central area, around Sorriso, the western area, around Campo Novo dos Parecis, and the south-eastern area, around Campo Verde and Ronodonopolis. The analysis of the evolution between 2000-2001 and 2006-2007 highlights three important phenomena: 1) the appearance of a fourth agricultural area in the eastern part of Mato Grosso, around Querencia (illustrated by the acquisition of a 80,000 ha farm by the Amaggi firm in

2003), 2) the expected merging of the two main agricultural areas (central and western regions) into one main agricultural region in the future, and 3) the crop expansion around the Xingu indigenous land (located in the north-eastern part of the State) where population may be affected by water pollution and deforestation issues.

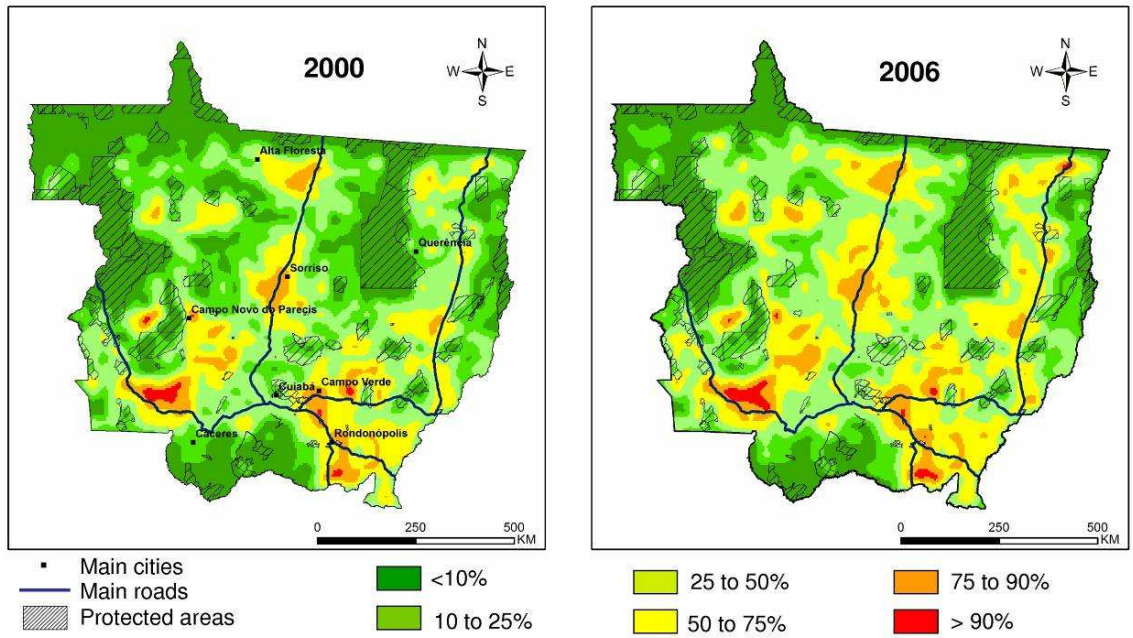

Figure 4. Evolution of the deforestation frontier in Mato Grosso between 2000 and 2006 (percentage of deforested area per area of 0.25°x0.25°).

The figure 6 highlights the rapid evolution of the intensification process in Mato Grosso. In 2000-2001, the double cropping systems (soybean followed by either corn or cotton) were only adopted in the surroundings of Sorriso and was not majority (less then 50% of the cultivated area was planted in double cropping system). On the contrary, in 2006-2007, double cropping systems were commonly used in the three main agricultural regions (central, south-western and south-eastern areas). In the central region (Sorriso), more than 50% of the total cropped area is intensively cultivated (this percentage reaches more than 86% in Lucas do Rio Verde). Such an expansion is partly due to the presence of efficient research institutes divulgating new practices to the soybean community and to the rainfall regimes (Arvor et al., 2010).

Finally, the figure 7 summarizes the information by proposing two maps representing the evolution of the agricultural frontier in Mato Grosso between 2000-2001 and 2006-2007. Only the protected areas and the Pantanal remain at the pre-settlement stage (and they should remain at this stage in the future). These protected areas are the most efficient way to struggle the agricultural frontier evolution. A major part of the state is at a non-agricultural occupation stage due to the fact that Mato Grosso is a recently colonized state, still in a process of incorporation to the national space, and also because cattle ranching remains the main land-use type after clearings. Then, deforestation is still going on and reaches more than 50% in inumerous areas. These areas form huge clearings from which the colonization process is evolving. Two of these clearings are located in the cerrado (south Mato Grosso, around Caceres and Rondonopolis) and didn't evolve so much during the study period. On the contrary, in the central area (around Sorriso), the colonization of the state is still evolving, and the agricultural expansion (mainly based on soybean crops) represents a major driving force. Few areas (near Sorriso) have reached the final intensive stage of the agricultural frontier, reminding that Mato Grosso is still experiencing a very active agricultural frontier.

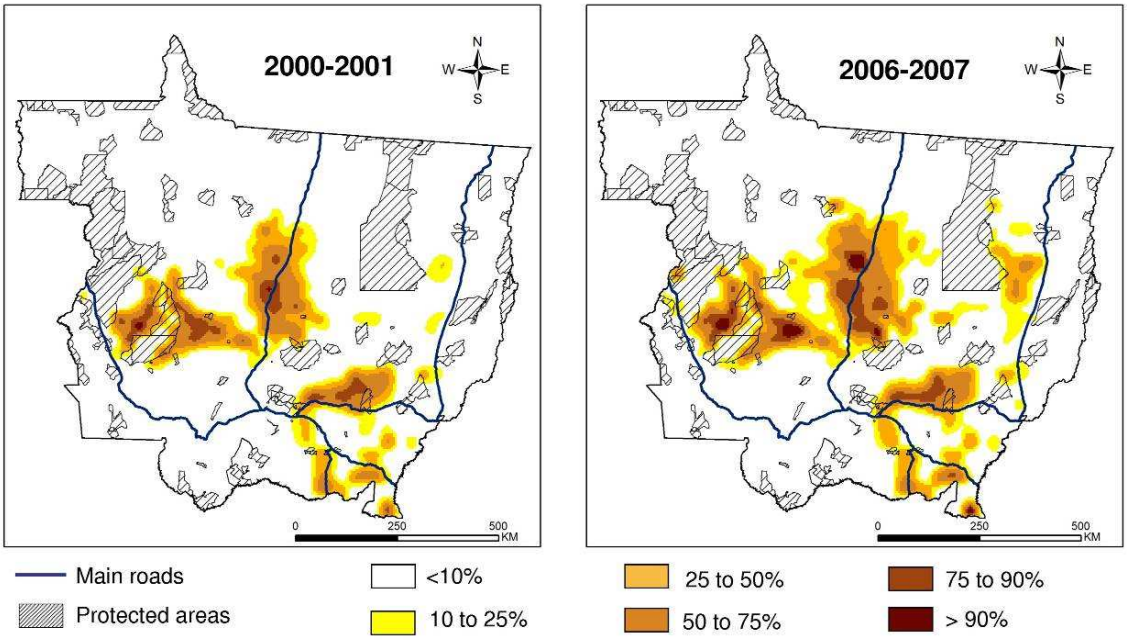

Figure 5. Evolution of the economic frontier in Mato Grosso between 2000 and 2006 (percentage of cropped area as compared to the deforested area).

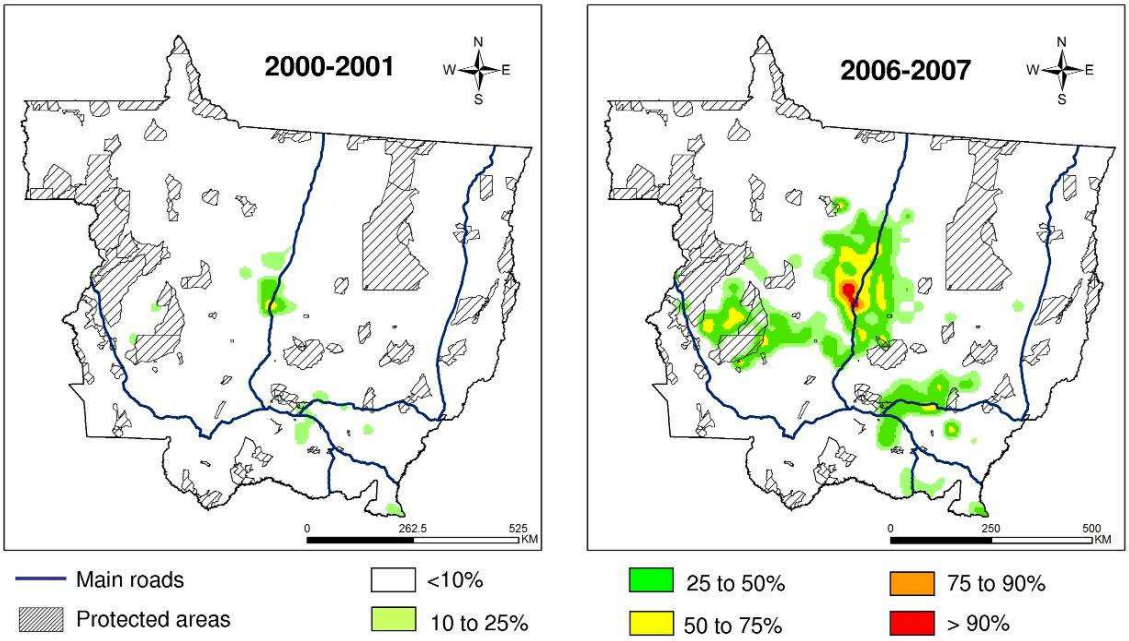

Figure 6. Evolution of the intensification frontier in Mato Grosso between 2000 and 2006 (percentage of cropped area with double cropping system as compared to the total cropped area).

4. Conclusion

Land-use changes observed in Mato Grosso attest the progress of the agricultural frontier in this State. The use of moderate resolution remote sensing data, as MODIS images, has already been proven to be efficientl for mapping and quantifying land-use changes in Mato Grosso. In this paper, we applied remote sensing techniques to better illustrate the concepts of the agricultural frontier in Mato Grosso. Our results allow to better visualize and understand how this frontier is evolving, either spatially or temporally.

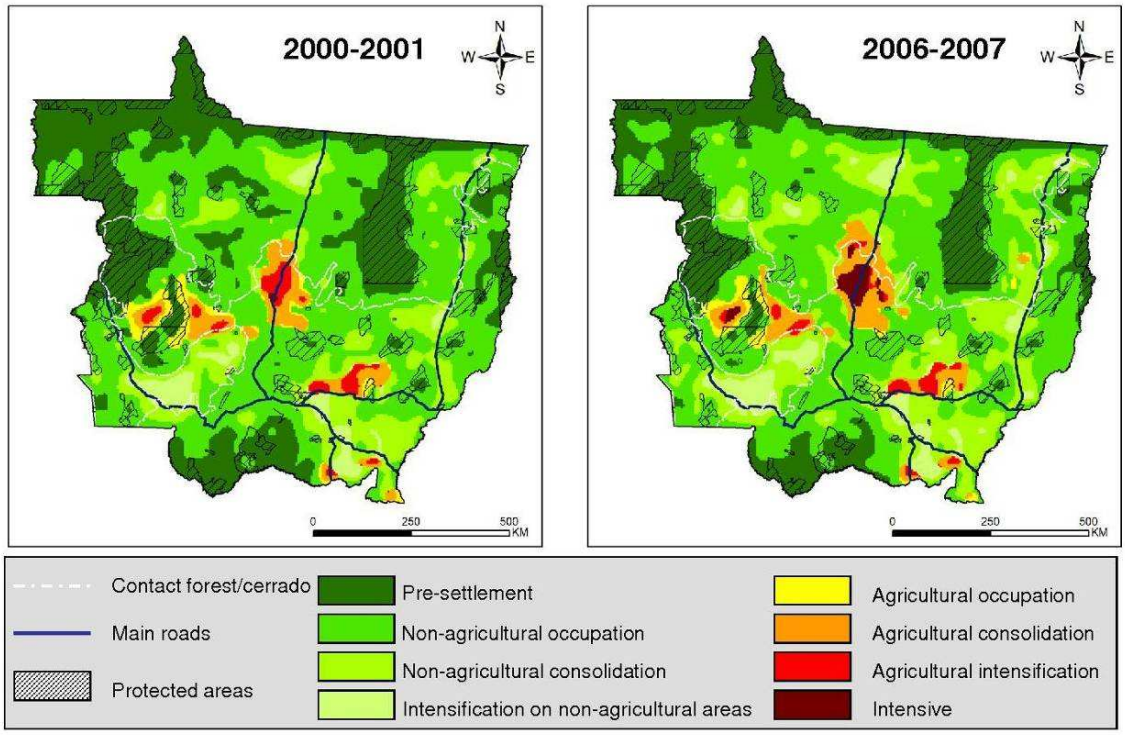

Figure 7. Map of the evolution of the agricultural frontier in Mato Grosso between 2000-2001 and 2006-2007 according to the land-use transition stages proposed in figure 3.

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