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Assessing the Spatial and Occupation Dynamics of the Brazilian Pasturelands Based on the Automated Classification of MODIS Images from 2000 to 2016

Leandro Parente * ** and **Laerte Ferreira

Image Processing and GIS Laboratory (LAPIG), Federal University of Goiás (UFG), Goiânia GO 74001-970, Brazil; laerte@ufg.br
* Correspondence: leal.parente@gmail.com; Tel.: +55-62-3521-1360

Abstract: The pasturelands areas of Brazil constitute an important asset for the country, as the main food source for the world's largest commercial herd, representing the largest stock of open land in the country, occupying ~21% of the national territory. Understanding the spatio-temporal dynamics of these areas is of fundamental importance for the goal of promoting improved territorial governance, emission mitigation and productivity gains. To this effect, this study mapped, through objective criteria and automatic classification methods (Random Forest) applied to MODIS (Moderate Resolution Imaging Spectroradiometer) images, the totality of the Brazilian pastures between 2000 and 2016. Based on 90 spectro-temporal metrics derived from the Red, NIR and SWIR1 bands and distinct vegetation indices, distributed between dry and wet seasons, a total of 17 pasture maps with an approximate overall accuracy of 80% were produced with cloud-computing (Google Earth Engine). During this period, the pasture area varied from ~152 (2000) to ~179 (2016) million hectares. This expansion pattern was consistent with the bovine herd variation and mostly occurred in the Amazon, which increased its total pasture area by ~15 million hectares between 2000 and 2005, while the Cerrado, Caatinga and Pantanal biomes showed an increase of ~8 million hectares in this same period. The Atlantic Forest was the only biome in which there was a retraction of pasture areas throughout this series. In general, the results of this study suggest the existence of two relevant moments for the Brazilian pasture land uses. The first, strongly supported by the opening of new grazing areas, prevailed between 2000 and 2005 and mostly occurred in the Deforestation Arc and in the Matopiba regions. From 2006 on, the total pasture area in Brazil showed a trend towards stabilization, indicating a slight intensification of livestock activity in recent years.

Keywords: MODIS; Random Forest; pasture mapping; Brazilian pasturelands dynamics

1. Introduction

Historically, food production was driven by population expansion, consumption and increased per capita income, which gradually raised the global food demand [1]. In this context, Brazil has tremendous importance for food production, as it is the largest world beef exporter [2] and is responsible for 35% of the world soybean exportation, considering grain and derived products [3].

This increase in the Brazilian agricultural production occurred by the conversion of natural ecosystems into planted pastures, mainly altering the Amazon [4] and Cerrado [5] biomes and through the soybean expansion over natural ecosystems and planted pastures [6,7]. Recent works have revealed a reduction in this extensification process, as converted areas are being intensified to produce both commodities [8,9]. Beyond its economic importance, this production has great potential in the

mitigation of greenhouse gas emissions [10,11], although only a small fraction of this potential can be achieved at a viable economic cost [12].

Considering the dynamics of the Brazilian agricultural land use, the pasturelands are an important asset for the country, occupying ~21% of its territory [13]; it can be used as both a land reserve [14] and as food for the herds containing ~218 million cattle [15]. Despite previous works having mapped these areas throughout the Brazilian territory [13,16], the absence of recurrent maps and the methodological differences between these initiatives make a temporal analysis of the Brazilian pasturelands difficult; its dynamics have important territorial, economic and environmental implications [17,18].

Faced with the challenge of systematic land cover and land use mapping on a large scale, the images provided by the MODIS sensor (Moderate Resolution Imaging Spectroradiometer) [19], (e.g., [20]), combined with new classification algorithms (e.g., [21]), made possible highly accurate and recurring representations of the Earth's surface (e.g., [22,23]). Specifically, this work uses MODIS data and a novel approach to produce annual pasture area maps for the entire Brazil. In addition, and based on our classification results, census data and socioeconomic statistics we conduct an analysis of the territorial dynamics of the pasture areas in the last 17 years, taking into account different aspects and characteristics of the Brazilian livestock.

2. Data and Methods

The pastureland mapping method, shown in Figure 1, was based on MODIS data, product MOD13Q1 Collection-6 [24,25] and on the supervised classification of spectral-temporal metrics. This approach, which is able to use several observations over one year to capture per-pixel seasonal responses, processed all of the images obtained over the Brazilian territory between 2000 and 2016, considering only the best observations (i.e., without cloud and cloud shadowing contamination), according to the MODIS pixel reliability [26].

The classification was performed on a yearly basis, considering a feature space with 90 spectral-temporal metrics, equally distributed between the dry and wet seasons (e.g., maximum red reflectance value in the wet season). These seasons were defined, pixel by pixel, through a percentile analysis of all NDVI values for one year, whereas all observations of the first quartile (≤25th percentile NDVI) were associated with the dry season and the rest of the observations (>25th percentile NDVI) were associated with the wet season. For each season, a minimum, maximum, amplitude, median and standard deviation were calculated considering the Red, NIR (near infrared) and SWIR2 (short wavelength infrared) band reflectance values and the spectral indices NDVI (normalized difference vegetation index), EVI2 (enhanced vegetation index) [27] and AFRI (aerosol free vegetation index) [28].

The classification approach used the Random Forest, an algorithm that considers several statistical decision trees to choose, based on a majority voting, a final class [29]. The training dataset, with the classes "pasture" and "not-pasture," was obtained from a Brazilian pasture map with per-pixel probability information based on Landsat 8 data obtained in 2015 [13], which was resampled to 250 m using the mode criterion. Considering the difficulty with sampling throughout the Brazilian territory, this training dataset was automatically produced using random points with larger (≥60%) and smaller probabilities (≤40%), according to the classes "pasture" and "not-pasture," respectively.

Due to the absence of reference pasture maps on other dates, the first classification was performed with training samples from 2015, assuming a stability scenario (i.e., without major land-cover and land-use changes). This scenario, even if hypothetical, allowed the annual production of preliminary pasture maps, with a per-pixel probability information and consequently the use of a single and consistent automatic sampling approach for the entire analysis period. Then, for each year and region of interest, a second classification was performed, considering the samples derived from the initial classification, using the same probabilities thresholds, that is, pasture (≥60%) and not-pasture (≤40%).

The training of a single classification model capable to generalize the Brazilian pastureland identification in the temporal and spatial dimensions is quite improbable, since these areas are very susceptible to climatic intra- and inter-annual variations [30] and present different biophysical and

management characteristics throughout the territory [31,32]. To handle this, the current study chose a geographical and temporal stratification approach, responsible for training models capable of capturing the regional characteristics and variability in a specific time window. The geographical stratification, based on the useful limits of the Landsat WRS-2 (World Reference System) tiles, avoided the use of a model, for instance, specific for the Pantanal pasturelands, to classify a region in the Atlantic Forest (Figure 1). Likewise, the temporal stratification considered a calendar year window, avoiding the use of a model, trained in 2010, for instance, to classify the same region in 2000. Thus, in total, 12,920 classification models were trained (i.e., 380 WRS-2 geographical regions, analyzed over 17 years in two classification phases), using a total of 2700 point samples for each model (comprising 500 trees), that is, 300 points extracted from the region of interest and eight adjacent regions (Figure 1).
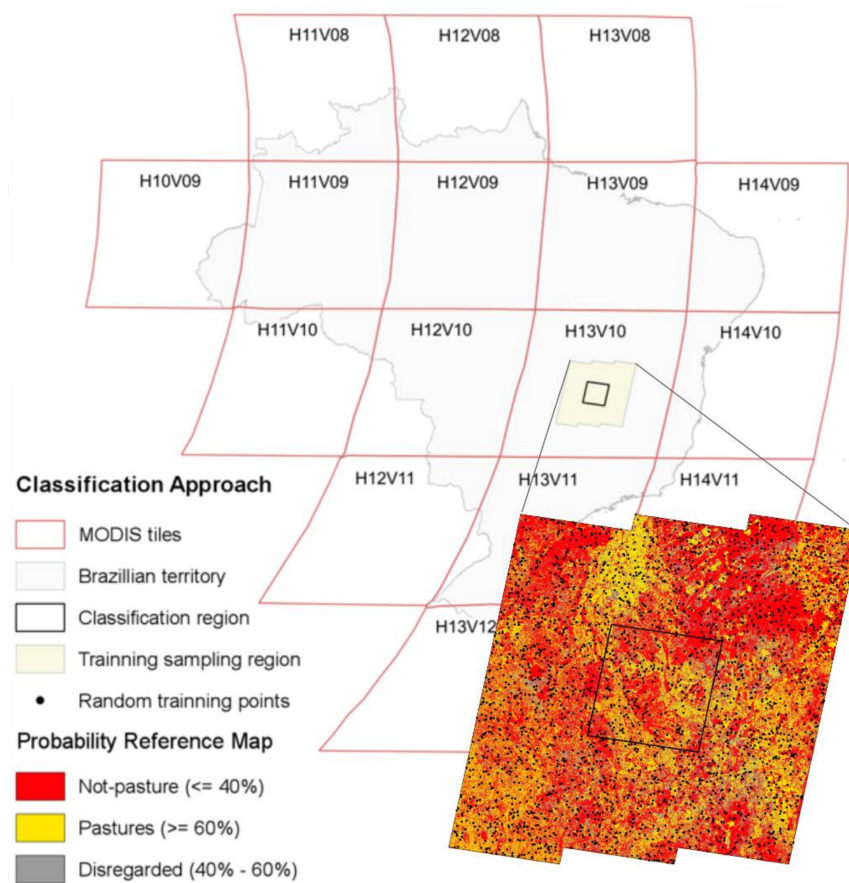

Figure 1. The stratified classification approach for mapping the Brazilian pasture areas, considering 16 MODIS tiles and the respective limits of 380 Landsat World Reference System (WRS)-2 regions. For each classification region, a total of 2700 training points (from the central WRS-2 path and row and eight neighboring regions), were randomly selected over a reference probabilistic map [13], considering both pasture (probabilities ≥60%) and not-pasture areas (probabilities ≤40%).

All steps described above were performed on Google Earth Engine, a cloud-computing platform capable of processing several remote-sensing analyses on a set of data and public images [33], using the python programing language (the scripts created within the scope of this work are available at: https://www.lapig.iesa.ufg.br/drive/index.php/s/NRP1VZ6kTyhh04i). The classification results, with the pasture class per-pixel probability, were exported to Google Drive. These were downloaded to a local workstation and combined to produce the annual pastureland maps for Brazil since 2000. The final maps of the pasture areas considered only the pixels with probability greater than or equal to 80%, used a majority rule filter to remove possible classification noises and discarded any pixels

located in fully protected [34], urban [34] and permanent water areas [35]. All post-classification steps were performed with the GDAL library [36].

The pasture mapping results were evaluated using 5000 random points, equally distributed into pasture and not-pasture areas, conservatively assuming that the minimum mapping accuracy was 50% and that the accuracy assessment error was 1% within a 95% confidence interval [37]. These points were visually inspected by five trained interpreters, who analyzed, for each point, 34 Landsat images acquired between 2000 and 2016 (i.e., two images per year, considering the dry and wet seasons), classifying each point according to 10 land-cover and land-use classes (i.e., pasture, crop agriculture, planted forest, native vegetation, mixed use, water bodies, urban area, mining and others). This assessment was conducted in the Temporal Visual Inspection Tool, which also considers the respective MOD13Q1 NDVI time series and high-resolution Google Earth images [38]. Using these points, the overall accuracy (which is a robust indicator for assessing the quality of binary classifications, that is, pasture and not-pasture) and the omission and commission errors were estimated for the pasture class, for each one of the 17 maps produced for Brazil.

The flowchart in Figure 2 depicts the main datasets and strategies used for the annual mapping of the Brazilian pasturelands, between 2000 and 2016.
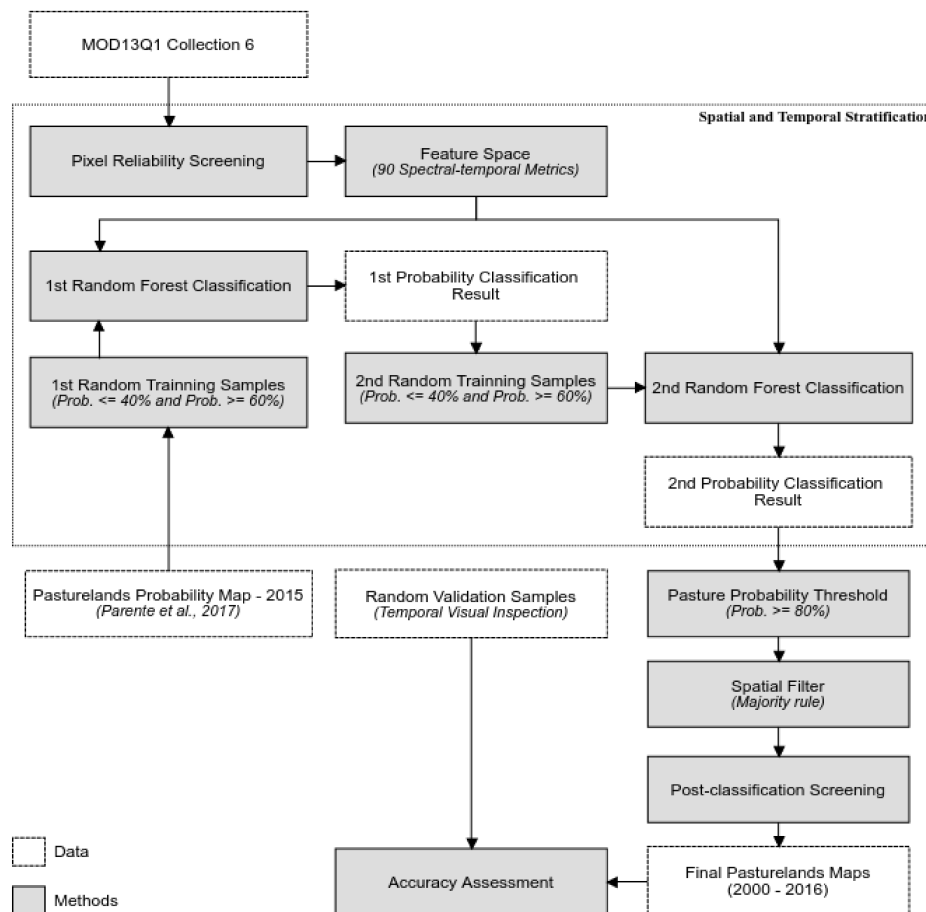

Figure 2. Methodological approaches used for mapping the Brazilian pasturelands between 2000 and 2016 based on MODIS data. The geographic stratification was based on the useful limits of the Landsat WRS-2 tiles, while the temporal stratification considered a calendar year window.

3. Results

The set of 17 Brazilian pasture maps (from 2000 to 2016), produced from the automated classification of MODIS images (Figure 3c), presented a relative convergence with existing mappings,

for the years 2002 (Figure 3a) [16] and 2015 (Figure 3b) [13], based on Landsat images. In this study, the pasture area mapped in 2002 and 2015 was ~169 and ~176 million hectares, respectively, while the Landsat-based mappings show, for the same years, ~149 and ~179 million hectares of pastures. In addition to these relatively close area values, the mapped areas have a very similar distribution pattern, which indicates that the proposed method is producing, in general, coherent and spatially consistent results, even though it is based on moderate spatial resolution data.
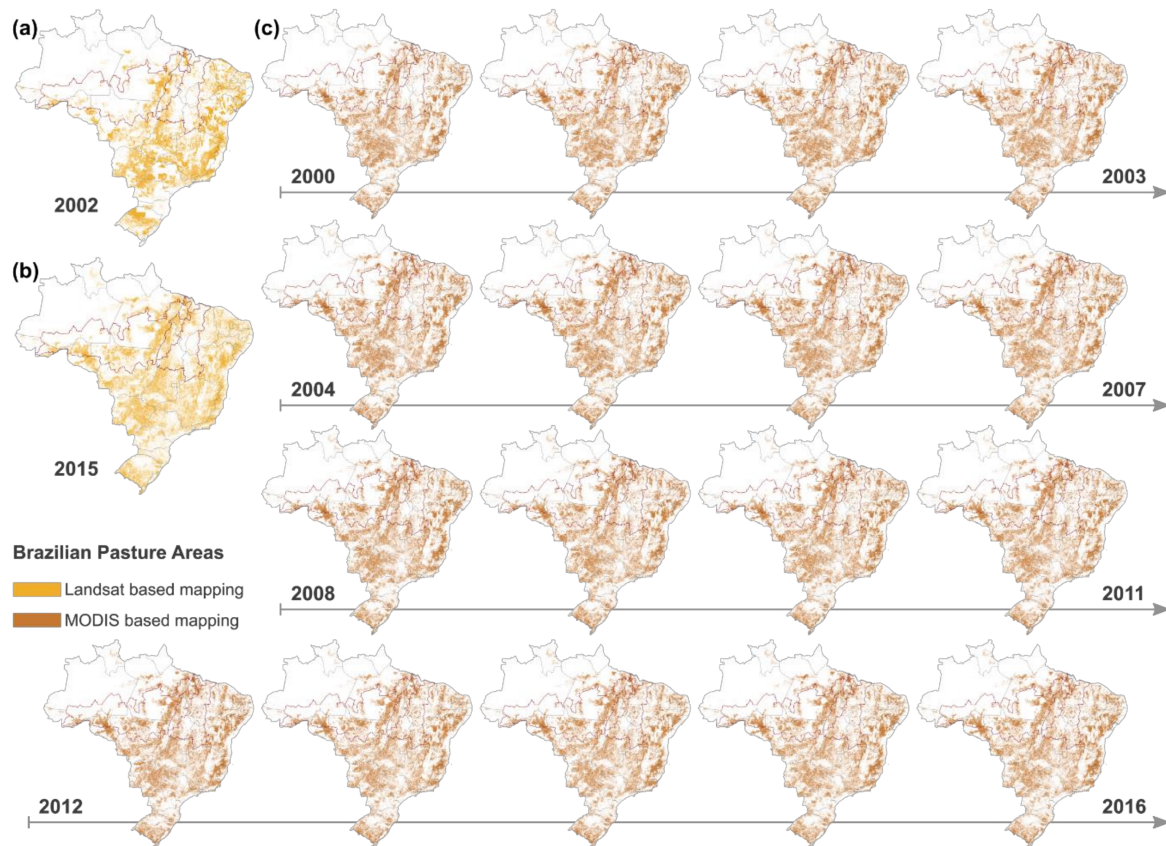
Figure 3. (**a**) The Brazilian pasture area as mapped by the segmentation and visual inspection of Landsat 7 images, with reference in 2002 [16]; (**b**) The Brazilian pasture area as mapped by the automated classification of Landsat 8 Images, with reference in 2015 [13]; (**c**) The Brazilian pasturelands time series, according to the automated classification of MODIS images obtained between 2000 and 2016.

In fact, for the entire time series, the pasture maps showed an overall accuracy of ~80% (Figure 4). In all years, the pasture class had a user accuracy (related to the commission error) greater than the producer accuracy, indicating that most of the mapping errors are related to pastures areas which have been omitted. According to this analysis, 2000 was the year with the largest mapping errors, while the highest time series accuracies were observed in 2010.
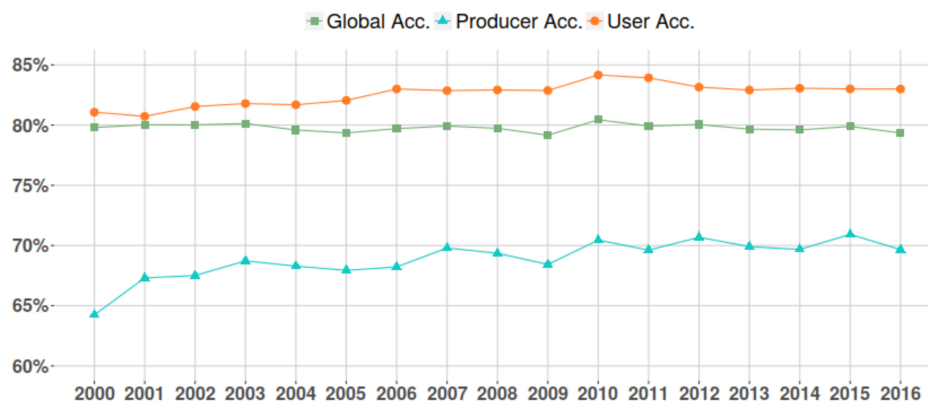
Figure 4. The accuracy assessment of the Brazilian pastureland mapping, considering 5000 random points, was inspected by five interpreters who considered 34 Landsat overpasses (two images per year), the NDVI-MOD13Q1 time series and high-resolution Google Earth images.

Our mapping revealed an increase of ~25 million hectares in the country's pasture area between 2000 and 2016; overall, ~80% of this increase occurred in the first six years of the analyzed period (Figures 3c and 5a). Most of this expansion occurred in the Amazon, increasing the biome pasture area by ~15 million hectares between 2000 and 2005, while in the Cerrado, Caatinga and Pantanal, the combined increased area, for the same period, was 8 million hectares (Figure 5b). The Atlantic Forest was the only biome that showed a retraction in pasture area throughout the analyzed time period, while the Pampa, a biome with a predominance of native grasslands, presented a relative stability over the years.

A temporal analysis of the Brazilian bovine herd, in animal units (AUs), also reveals an expressive increase in the first six years of the same period, starting at 125 million AU in 2000 and reaching 152 million AU in 2005 (Figure 5a). The animal unit calculation—1 AU is equivalent to 450 kg of live animal weight—considered the cattle herd composition, produced by the Agricultural Census for the year of 2006 only [39]—and which was assumed constant for other years—and the absolute number of cattle heads, estimated on a yearly basis by the Municipal Livestock Research [15]. The ratio between the AU and the pasture area showed a variation of 0.1 AU/hec in the Brazilian bovine stocking rate (over the last 17 years), which reached its lowest value in 2001 with 0.8 AU/hec and its peak in 2016, with 0.9 AU/hec. These results suggest the prevalence of an extensification process in the first years of the series, followed by a slight intensification of pasture areas in recent years (Figure 6).
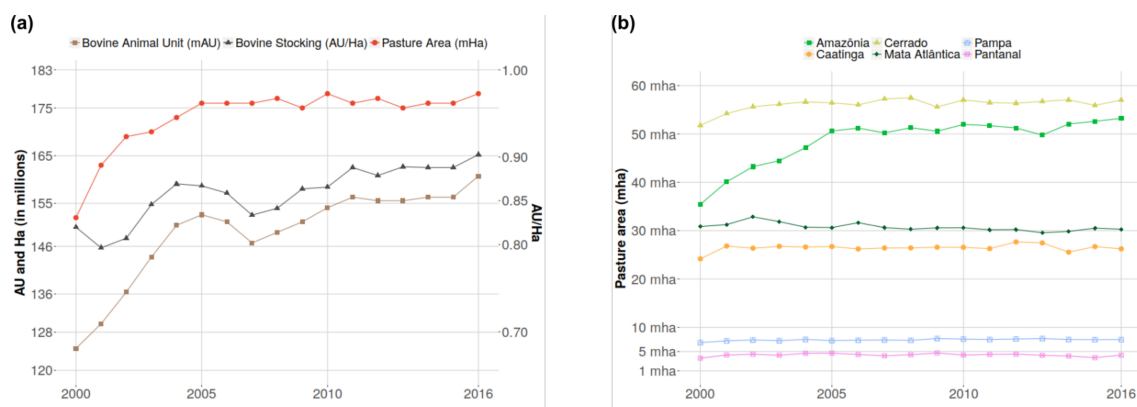
Figure 5. (**a**) Pasture area in Brazil, bovine animal unit (considering the composition and size of the herd) and Brazilian stocking rate time series; (**b**) Time series of the pasture areas in the six Brazilian biomes.

According to these mapping results, Pará was the state with the greatest pasture area expansion, equivalent to 8.2 million hectares (i.e., 6.61% of its territory), followed by Mato Grosso, Bahia, Maranhão and Rondônia states, with 4.6, 2.7, 2.4 and 2.2 million hectares of new areas, respectively (Figure 6). Considering these states, the municipalities that are responsible for this process are located in agriculture frontiers, such as the Deforestation Arc in the Cerrado and Amazon borders [4] and the Matopiba, in the Cerrado biome [40]; moreover, most of this extensification process occurred until 2005.
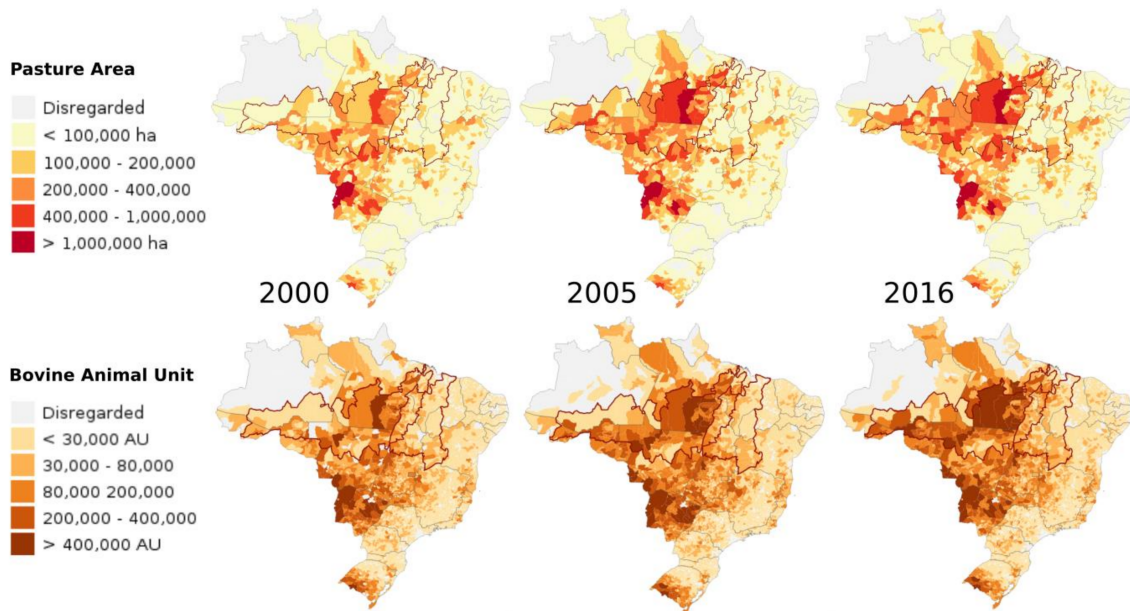

Figure 6. Geographic distribution of the mapped pasture and bovine animal unit, at the municipal basis, depicting the increase of both until the year 2005 and a subsequent intensification process, with stabilization of the pasture area and an increase in the number of cattle.

Within the same period, the only states in which there was a decrease in the absolute values of pasture areas were São Paulo, Paraná, Paraíba and the Federal District, being numerically inexpressive in the last two states. The São Paulo state reduced pasture areas by almost 2.4 million hectares (i.e., 9.62% of its territory), while a contraction of 0.4 million hectares was observed in Paraná. This analysis, at the municipal basis, reveals that none of the five municipalities with the greatest pasture area reduction—Rosário do Oeste (MT), Três Lagoas (MS), Rio Verde (GO), Sorriso (MT) and Nobres (MT)—are located in the São Paulo and Paraná states. This result suggests the existence of a spatial dynamic for the Brazilian pasture, intra- and inter-state, which displaces the land use of these areas to other municipalities according to the production needs and agricultural activity of the country.

4. Discussion

The relative stability of the accuracy values (Figure 4), in particular the overall accuracy, indicates that the proposed method is capable of producing comparable maps, which are spatially and temporally consistent. Nevertheless, these maps are subject to commission and omission errors. In part, the commission errors were minimized by the use of filters and masks, such as the water mask, which was used to remove pixels with high sediment concentration, wrongly classified as pasture (and mostly located in rivers of the Amazon biome). On the other hand, the more significant omission errors are related to the spatial resolution of the MODIS pixels (~6.25 hectares), which is not very compatible with the detection of small pasture fragments, usually on slope regions, especially located in east of the Serra do Espinhaço (Minas Gerais) and in the Serra Gaúcha (Rio Grande do Sul).

Despite these spatial resolution limitations, the MODIS MOD13Q1 data presented a high availability of observations free of clouds and cloud shadows (Figure 7), which provided denser time series for the generation of spectral-temporal metrics, enabling the appropriate capture of seasonal variations in pasture areas in the classification models. Considering the entire Brazilian territory, between 2000 and 2016, there was an average of ~18 MODIS good observations per pixel, a value which is relatively close to its full temporal resolution (i.e., 23 observations).
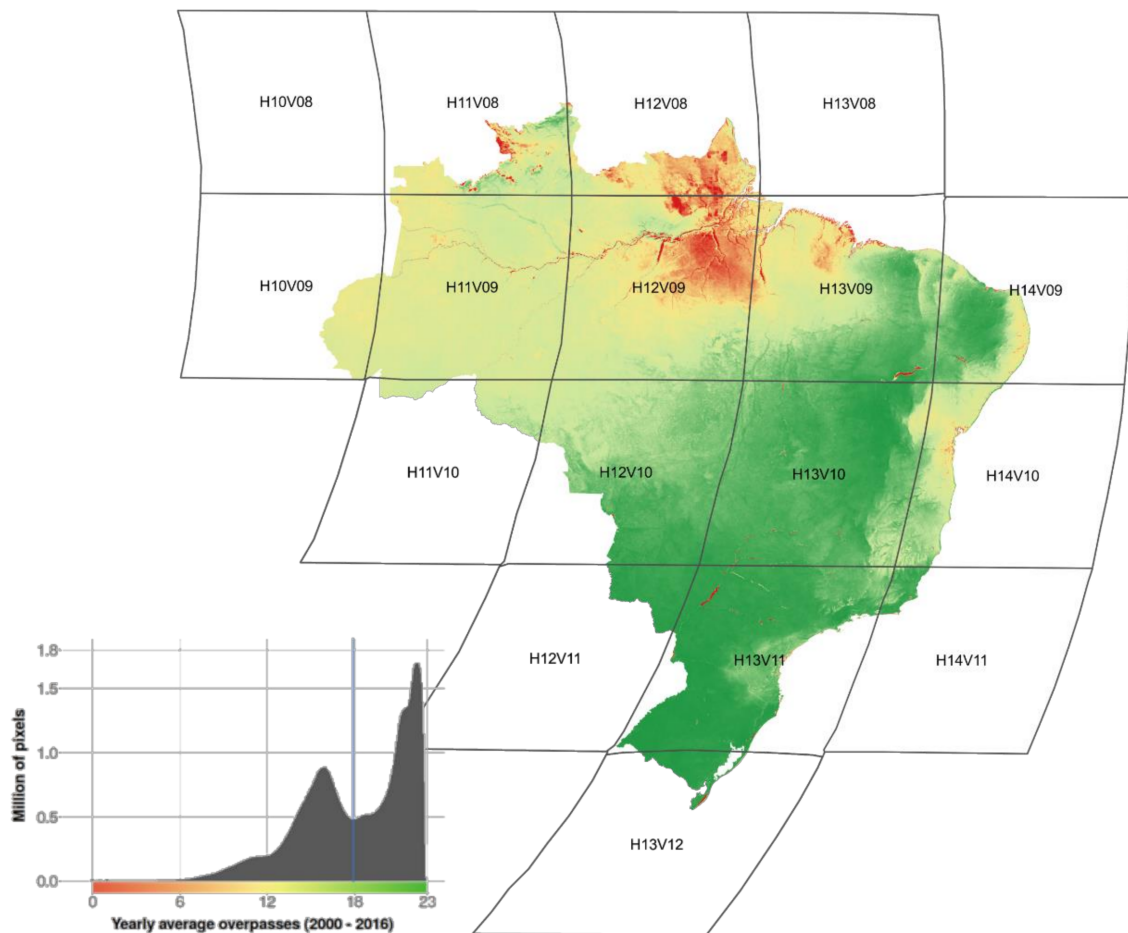

Figure 7. Annual average of MODIS observations considering only the best quality pixels (i.e., values 0 and 1, according to the pixel reliability image) in the period of 2000 and 2016. The blue line represents the average value of MODIS observations for the entire Brazilian territory during the same period.

In general, the results produced by this study suggest the existence of two relevant moments regarding the occupation of the Brazilian pasture areas. The first, strongly supported by the opening of new grazing areas, prevailed between 2000 and 2005 and mostly occurred in the regions of the Deforestation Arc and Matopiba. From 2006 on, the total pasture area in Brazil tended to stabilize and a correlation with bovine herd data suggested a mild intensification process, which enabled production increases, in animal units, on the same portion of land which was already opened. This hypothesis is reinforced by the ability of the pasture areas to model, on a municipal basis, the bovine animal unit values (Figure 8). Despite the good correlations between very distinct datasets (i.e., remote sensing and census data) and complementary periods, this analysis disregards the spatial dynamics of pasture areas. The process of converting older pastures to crop areas may have occurred, for instance, in the Matopiba municipalities, forcing the opening of new grazing areas for livestock, without any substantial changes in the region's pasture area balance. The spatial distribution of areas can vary

at the intra- and inter-municipal level, according to market demand [41], infrastructure aspects [42] and land competition among the various productive sectors of society [43].
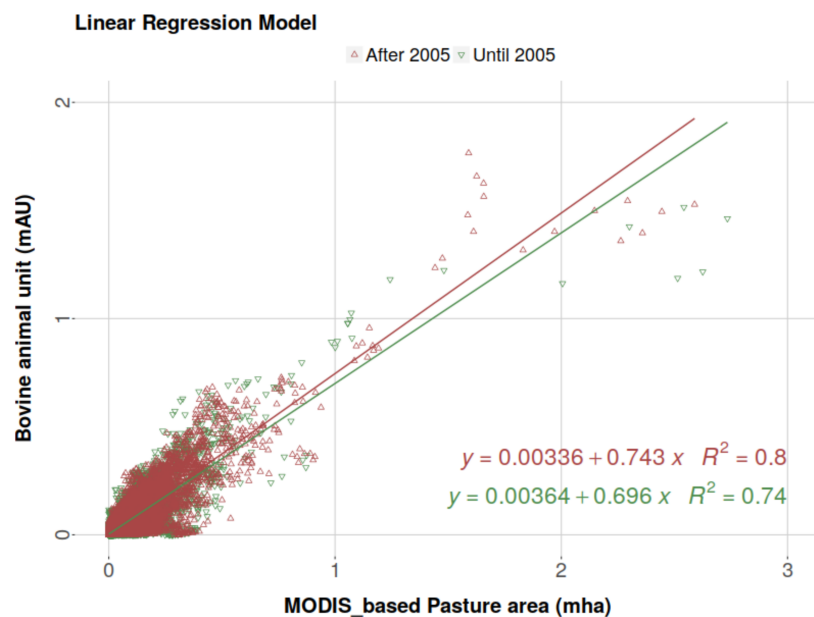

Figure 8. Linear regressions between pasture areas (based on MODIS data classification) and bovine animal units for all municipalities in Brazil, in two complementary periods (2000 to 2005 and 2006 to 2016).

Looking for a better understanding of these spatial dynamics, a linear regression was adjusted between the (MODIS based) pasture area and the cattle herd (considering the last 17 years) for each Brazilian municipality, which allowed a correlation spatialization between these variables, through the resulting goodness-of-fit ($R2$). This approach also considered the slope of both variables, calculated by their linear regressions against time. The combination of these several linear models revealed a set of municipalities relevant to the livestock activity, in which the expansion and retraction of pasturelands is historically related to the municipality's bovine animal unit (Figure 9). This analysis exposed a strong migration trend of the Brazilian livestock from center-south to the north, in a relatively short period—less than two decades—although the infrastructure—federal roads network [44] and slaughtering houses [45]—has remained in the center-south portion of the country. A probable consequence of this migration was the increase in beef production cost due to the transportation of the animals to slaughterhouses in the termination phase, possibly offset by the lower land's price in the identified livestock expansion zone [46,47].

All of the "top-5" pastureland increasing municipalities—São Félix do Xingu (PA), Altamira (PA), Novo Repartimento (PA), Porto Velho (RO) and Novo Progresso (PA)—are in the expansion zone, mostly concentrated in the Deforestation Arc and in the Matopiba, which indicates a pasture expansion over native vegetation areas of the Cerrado and Amazon in the last 17 years. Several studies have analyzed the environmental impacts and socioeconomic benefits resulting from the conversion of native areas to agricultural areas [48–50]. However, in the context of recent Brazilian livestock dynamics, the benefits appear to be less expressive than the impacts, since in 2010, several municipalities located in the expansion zone presented HDI (human development Index—[51]) levels smaller than, or close to, the general levels of the retraction zone in 2000 (Figure 10). Even with HDI increases of these municipalities in the same period, the livestock migration to the north shifted the cattle ranchers away from consumer markets, both internal and external, consolidating them in a portion of the territory with a lack of infrastructure and inducing various environmental impacts [52,53].
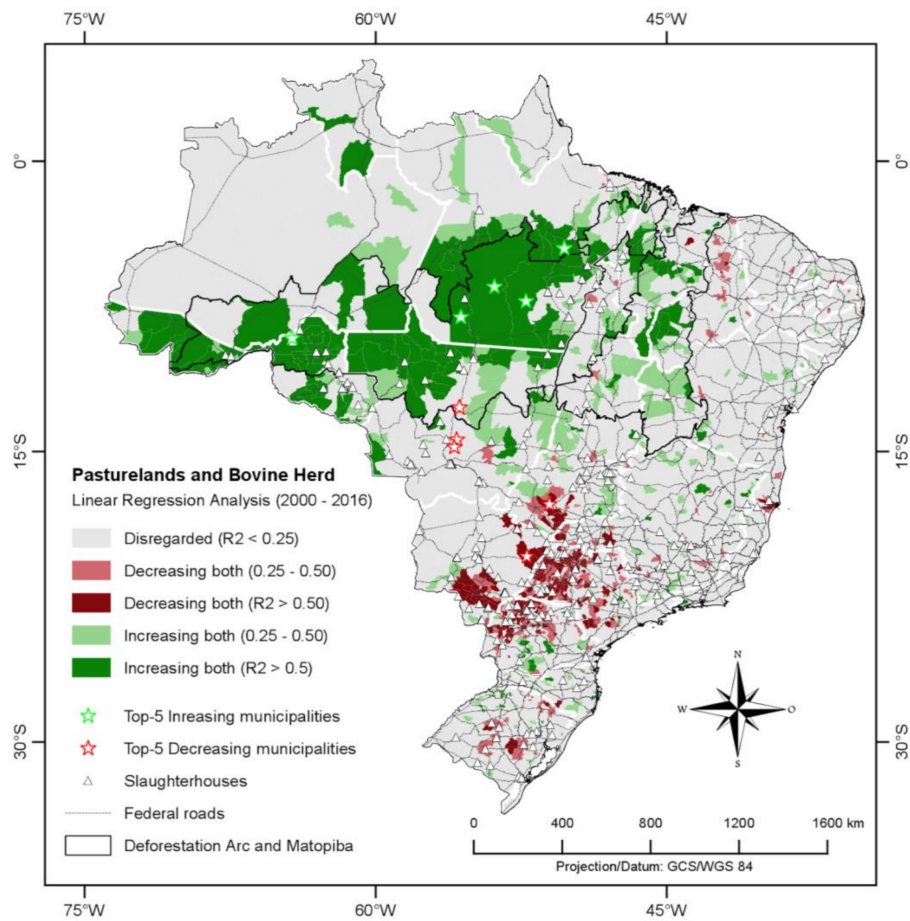
Figure 9. The expansion (green colors) and retraction (red colors) zones of the Brazilian livestock activity, produced through several linear regression models between the MODIS based pasture areas and the cattle animal unit at the municipality level (available at: http://maps.lapig.iesa.ufg.br/?layers= pa_br_correlacao_pastagem_ua_250_na_lapig).
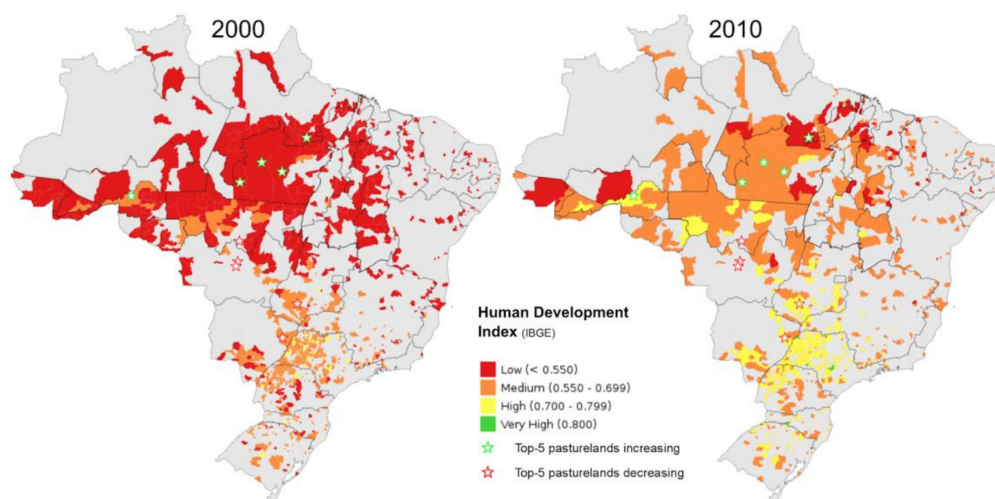
Figure 10. 2000 and 2001 Human Development Index (HDI) values of the municipalities located in the expansion and retraction zones of the Brazilian livestock activity.

One of the probable causes of this process was the pressure for already opened lands in the central south of Brazil, due to the production demand of other commodities, such as soybeans, sugarcane and wood. The replacement of livestock activity in this region increased the HDI from medium to high. In the north of Paraná and in the west of São Paulo, the main driver of this process was the rapid expansion of sugarcane cultivation [54], as well as in part of southeastern Goiás [55]. The decrease in livestock activity and the increase in the HDI of Três Lagoas-MS—the Brazilian municipality that lost the second most pasture area in the analyzed period—is justified by its consolidation as a relevant silviculture pole and by the installation of two large cellulose plants [56]. In the southeastern of Goiás, livestock activity was also replaced by grain cultivation [57], which justifies the presence of Rio Verde-GO—the Brazilian municipality that lost the third most pasture area in the analyzed period—in the identified retraction zone.

The retraction of pastures in the rest of the "top-5" pastureland decreasing municipalities, located in Mato Grosso, is driven by the grain cultivation expansion in the state, mostly soybean [58]. Interestingly, only Sorriso-MT had a decrease, even from 2010, of the bovine herd. The increasing trend of animal units, observed in Rosário do Oeste-MT and Nobres-MT, may indicate a livestock intensification close to these municipalities. The reduction of pastures and the availability of machinery and agricultural products, consolidated by the cultivation of grains, may have forced an intensification of the beef production in the region, through more efficient [59] or rotating [60] productive systems.

5. Concluding Remarks

This study used a unique automated methodological approach to produce, based on the Random Forest classification of MODIS images, a temporal series of 17 pasture maps for the entire Brazil (2000–2016). With an overall accuracy of ~80% and consistent spatial-temporal trends, the mapped area varied from ~152 million hectares in 2000, to ~178 million hectares in 2016, a pattern that is consistent with the cattle herd increase and prevalence of production growth through the conversion of new areas.

Specifically, the analysis of these maps revealed that there was a strong expansion of pasture areas in the first five years of the series, mostly in the Cerrado and in the Amazon. From 2005 on, the area balance stabilized and the livestock activity showed a slight intensification process, increasing its bovine stocking rate by 0.1 AU/hec in the entire analysis period. The high correlation of the cattle herd with the pasture areas, on a municipal basis, revealed a migration trend of livestock activity from the center-south to the north of the country, probably caused by the production needs of other Brazilian commodities, which demand greater infrastructure and are more economically attractive.

Despite the recent growth of the Brazilian livestock—currently, the country is the largest beef exporter in the world—the dynamic revealed by this study shows a displacement of the cattle ranchers from consumer markets, both internal and external and their consolidation in municipalities with a lack of infrastructure, at a high environmental cost. In this respect, the country demands public policies capable of improving the infrastructure and mitigate new environmental impacts in the north region. Public policies such as the ABC Plan (low carbon agriculture) can encourage sustainable management practices in regions with extensification history, like the Pará state, avoiding the opening of new pasture areas to meet the future beef production demand. On the other hand, productive intensification policies can focus on regions which already have an agricultural production infrastructure, such as the center of Mato Grosso, thereby reducing its implementation time. The effectiveness of these and other related public policies has great potential to meet the climate commitments signed by Brazil in the COP 21 and to promote the better utilization of the Brazilian territory.

Author Contributions: L.P. and L.F. conceived the idea of the study; L.P. processed the data and, together with L.F., analyzed the results; L.P. and L.F. contributed to the discussions, writing, and revision of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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