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Shaping the Brazilian landscape: a process driven by land occupation, large-scale deforestation, and rapid agricultural expansion

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ABSTRACT

Brazil is one of the largest food producers in the world, a leading role that prompted a profound process of anthropization of its landscapes. Knowing the dynamics and dimension of these transformations is essential for a more efficient and sustainable use of the country's natural resources. Thus, in this study we present, based on an unprecedented sample design and interpretation of 85,152 sample points in Landsat images, the area estimates of the main land cover and land use classes in Brazil, as well as their annual transitions, from 1985 to 2018. Our results indicate that, of the 850 Mha that comprise the national territory, 294.2 Mha $\pm$ 1.44% were anthropized in 2018, with ~34% of this area converted after 1985. In this period, there was a loss of 98.2 Mha $\pm$ 2.27% of natural vegetation, and an increase of 55.1 Mha $\pm$ 0.64% in the pasture areas and 28.2 Mha $\pm$ 0.29% in the areas of annual crops. The transition analysis showed that 83.07 Mha $\pm$ 1.31% of pastures and 9.64 Mha $\pm$ 0.45% of agriculture (annual, semi-perennial, and perennial combined) occurred over natural vegetation, 18.12 Mha $\pm$ 0.63% of pastures were converted to agriculture, while another 9.7 Mha $\pm$ 0.45% were abandoned, which can serve as important land reserves for other uses. The vast public dataset, approaches (simple, robust, and straightforward), codes and tools (open and available) utilized in this study can be easily employed in any other region of the world, in support of environmental monitoring and improved territorial governance practices.

Introduction

The increase in the global demand for food has promoted Brazil to a prominent role as one of the largest grain and beef producers in the world^{1,2}. The soy produced in the country represents 23.4% of the global production and 30.6% of the global exports³, being an important vector of economic, social, and environmental transformations in the country's recent history. Thus, intense changes in land use and land cover, triggered by state and private actions, occurred from the 1970s onwards⁴. In the Cerrado biome, for example, agricultural expansion resulted in the suppression of more than 50% of the native vegetation cover and the fragmentation of a large portion of its remnants, as well as socio-territorial impacts, such as the migration of a large part of the rural population for cities^{5,6}. Another biome heavily impacted by agricultural expansion was the Amazon⁷⁻¹⁰, with the incidence of a similar conversion process of native vegetation in pasture and soybean intensified from the 1980s.

Considering the effects of these actions and global climate change^{11,12}, the territorial governance that prioritizes environmentally sustainable agricultural production and the execution of environmental policies that seek to the conservation of natural resources become even more important. In this context, a great ally in the formulation and monitoring of these policies are land use and land cover data. They ensure greater efficiency in economic, social, and environmental diagnoses, supporting the prioritization of actions and goals in the short, medium, and long term.

Much of the data that quantify the areas occupied by native vegetation, agriculture, and other land uses in the Brazilian territory are derived from census estimates or produced from satellite data. These include public efforts such as the Agricultural Census, the Municipal Agricultural Research (PAM), the mappings produced by the Brazilian Institute of Geography and Statistics (IBGE), programs coordinated by the Ministry of the Environment (e.g. Probio and Terraclass), in addition to monitoring systems for the suppression of native vegetation in the Brazilian biomes, coordinated by the National Institute for Space Research (INPE) (i.e. PRODES and DETER^{5,13}).

These mappings and monitoring systems have in common the production of data from the visual inspection of satellite images, involving high costs for relatively short time frames. Recently, with the increase in computational capacity for processing and storing data, some mappings for the Brazilian territory started to be carried out using machine learning algorithms, including initiatives such as Mapbiomas⁷ and Global Forest Watch^{14,15}. Although spatially explicit, such mappings should not be used, directly and as the only data source, to estimate land use and land cover areas and their respective transitions, since classification errors result in biased estimates¹⁶.

Alternatively, such area estimates should consider point samples, supported by sampling designs and labeled by visual inspection of satellite images^{17,18} or field surveys^{14,19}. Such approaches, however, are not free from the bias of subjectivity and the criteria of each interpreter, the occurrence of eventual georeferencing errors or, depending on the image resolution, the presence of pixels with spectral mixing²⁰. On the other hand, the synergy between spatially explicit mappings, based on the use of automated classifiers, and point samples is necessary, either for validation purposes or for area adjustments^{5,14,19,20}.

With regard to the use of point samples, the option for stratified sampling is frequent, whose strata are defined by existing mappings, which may or may not correspond to the classes of interest^{9,18,21,22}. In this context, this work presents, based on point samples derived from the interpretation of Landsat images, the estimate of the total area of 13 land cover and land use classes in Brazil between 1985 and 2018. For this endeavor, we adopted an unprecedented sample design, which, while consistent with the stratification assumptions, proved to be sufficiently robust and spatially stable over time, thus allowing area estimates of land use and land cover changes, specifically concerning deforestation and agricultural expansion, on a national scale and for all the Brazilian biomes.

Results

Land Use and Land Cover Dynamics

Land use and land cover area estimates revealed a gross loss of 49.1 Mha $\pm 0.73\%$ of forest formations, 43.3 Mha $\pm 0.53\%$ of savanna formations, and 12.5 Mha $\pm 0.37\%$ of grassland formations between 1985 and 2018, a total of 104.8 Mha $\pm 1.63\%$ of natural vegetation (Figure 1a). In relative numbers, savanna formations were the most affected, with a 30.4% $\pm 0.53\%$ reduction in vegetation cover based on the initial year of analysis (1985), followed by grassland formations with 21.4% $\pm 0.37\%$, and forest formations with 11.4 % $\pm 0.73\%$ reduction in the same period. Areas of other non-forest formations, located mostly in the Amazon biome, remained stable, with variations in the initial and final years caused by samples labeled as "not observed" due to the high occurrence of clouds in the region, a problem that is also observed in the estimates of forest formations.

With regard to land use estimates, there was an area increase of 55.1 Mha $\pm 0.64\%$ for pasture, 28.2 Mha $\pm 0.29\%$ for annual crop, 7.7 Mha $\pm 0.14\%$ for semi-perennial crop, 7.5 Mha $\pm 0.15\%$ for tree plantation, and 2.1 Mha $\pm 0.10\%$ for perennial crop (Figure 1). Although the largest increase in area was associated with the expansion of pastures, in relative numbers this was the land use with the lowest relative percentage of expansion with reference to 1985, equivalent to 34.5% $\pm 0.64\%$, while practically all other land uses have doubled the area of occupation between 1985 and 2018. The relative increase of perennial crops was equivalent to 99.1% $\pm 0.10\%$, of annual crops was 156.4% $\pm 0.29\%$, of tree plantation was 173.2% $\pm 0.15\%$, and of 183.6% $\pm 0.14\%$ for semi-perennial crops.

Specifically on the urban infrastructure estimates, there was an absolute area increase of 1.7 Mha $\pm 0.11\%$ and a relative increase of 57.3% $\pm 0.11\%$ over the 34 years evaluated (Figure 1b). The annual expansion of these areas showed the same trend as the expansion of perennial crops. The country's water surface increased 1.3 Mha $\pm 0.18\%$ in absolute numbers and 10.2% $\pm 0.18\%$ in relative terms, while the wetlands area decreased by 0.26 Mha $\pm 0.10\%$ in absolute numbers and 8.6% $\pm 0.10\%$ in figures relative to 1985. The absolute area occupied by the "Other" class (i.e. rocky outcrop, apicum, aquaculture, mangrove, mining, other non-vegetated areas, beaches and dunes) increased by 0.9 Mha $\pm 0.11\%$ and by 23.1% $\pm 0.11\%$ in relative numbers.

Historical Deforestation

Estimates of primary deforestation (i.e. first event of vegetation suppression considering a predefined baseline year) revealed a total accumulated area equivalent to 98.2 Mha $\pm 2.27\%$, of which 52.7 Mha $\pm 0.99\%$ occurred in forest formations, 35.03 Mha $\pm 0.82\%$ in savanna formations, and 10.4 Mha $\pm 0.46\%$ in grassland formations, between 1988 and 2018 (Figure 2a). Despite the general downward trend in deforestation estimates in the period evaluated, in 2018, 1.9 Mha $\pm 0.05\%$ of natural vegetation cover was suppressed, mostly affecting forest formations. The years 1989 and 2003 presented the highest estimates of primary deforestation in the period, with areas equivalent to 5.79 Mha $\pm 0.10\%$ and 5.03 Mha $\pm 0.09\%$, respectively.

With regard to the Brazilian biomes (Figure 2b), the Amazon was the most affected biome, with 37.2 Mha $\pm 1.96\%$ of total primary deforestation between 1988 and 2018, followed by the Cerrado biome with 36.9 Mha $\pm 3.23\%$. This total was 5.4 Mha $\pm 2.0\%$ and 11.8 Mha $\pm 4.1\%$ for the Atlantic Forest and Caatinga, respectively. Despite the downward trend in the period, the Pampa and Pantanal showed relative stability in areas of primary deforestation, with an annual average of ~162,068 ha and ~70,344 ha, respectively, in the 34 years evaluated.

Agricultural Expansion

Our results indicated an increase of 83.07 Mha $\pm 1.31\%$ of pastures and 9.64 Mha $\pm 0.45\%$ of agriculture (annual, semi-perennial and perennial combined) over natural vegetation, while 105.2 Mha $\pm 0.25\%$ and 16.6 Mha $\pm 0.16\%$ of pastures and agriculture, respectively, remained with stable use between 1986 and 2018 (Figure 3a). Of the existing pastures in 1986, 18.12 Mha $\pm 0.63\%$ were converted to crops and 9.7 Mha $\pm 0.45\%$ were abandoned, showing a high presence of secondary vegetation in 2018. Most of the expansion of pastures occurred in the Amazon, equivalent to 33.9 Mha $\pm 1.98\%$ (Figure 3b), followed by 30.7 Mha $\pm 3.08\%$ in the Cerrado (Figure 3c). On the other hand, most of Brazil's crop expansion has taken place in the Cerrado, equivalent to 13.05 Mha $\pm 2.81\%$, with ~60% being over pasture areas and the rest over natural vegetation. In the Atlantic Forest, ~94% of the crop expansion occurred over pastures, equivalent to 9.1 Mha $\pm 2.69\%$ (Figure 3d), while in the Pampa, 2.84 Mha $\pm 9.02\%$ occurred over natural vegetation (Figure 3f), mostly in grassland formations. In the Caatinga and Pantanal, pasture expansion occurred over 11.6 Mha $\pm 4.28\%$ (Figure 3e) and 2.19 Mha $\pm 9.63\%$ (Figure 3g) of natural vegetation, respectively, affecting mainly the savanna and grassland formations in these biomes.

Discussion

The data produced by this study show that, between 1985 and 2018, Brazil reduced its natural vegetation area by 98.2 Mha $\pm 2.27\%$, increasing its agricultural area by 93.3 Mha $\pm 0.52\%$ (Figure 3), a land conversion unparalleled in the world for the period in analysis¹⁴, whose driving forces are intrinsically associated with global demands for soy and beef^{23–26}. Although most of this conversion, in absolute area, is due to the expansion of pastures, in relative numbers the crop area of the country almost doubled in the same period, with an expansion predominantly in the area of consolidated pastures (existing in 1985 - Figure 3a). This dynamics of land occupation is common in the country⁹, since pastures, due to their low initial investment, occupy extensive areas located in regions with little infrastructure, which, if favorable to mechanization, tend to give space to crops in the following years²⁷.

Our estimate of land use and land cover indicated a linear growth of the Brazilian pastures until the year 2005, and a subsequent stabilization in absolute area until the end of the analysis period (Figure 1a). However, when analyzing the agricultural expansion in Brazil, it is possible to note that the conversion of natural vegetation to pasture continued even after 2005, while the conversion from pasture to crops increased in the same period (Figure 3a), an indication that the stabilization observed may be related to the balance between the area of expansion and retraction of pastures, resulting in an absolute balance close to zero in the most recent years of the series.

In this sense, in spite of the reduction of deforestation in Brazil (Figure 2a), the expansion of pasture is still responsible for a large part of the conversion of natural vegetation in the Cerrado and Amazon biomes (Figure 2b), a fact that can be explained by development-oriented policies installed in Brazil in the mid-1970s⁴, and the low value of deforested land in agricultural frontier areas²⁸. On the other hand, most of the expansion of agricultural area in the country took place on consolidated pastures, in the Cerrado biome and in the Atlantic Forest, responsible for most of the production of grains and sugarcane^{9,29}. Such land use conversion favored the adoption of new technological standards (i.e. more intensive systems with greater return to the producer) by ranchers located in these regions^{30,31}.

This conversion dynamic, however, did not affect most of the country's consolidated pastures, as our results indicate that 105.2 Mha $\pm 0.25\%$ of the Brazilian pastures did not show any change in land use between 1985 and 2018. These areas are likely to be found in regions with low agricultural suitability, thus having a lower opportunity cost related to an eventual conversion to soybean, given the limitations imposed by environmental and infrastructure conditions^{32–34}.

With regard to deforestation, our results indicate that forest formations were the most affected in absolute area (52.7 Mha $\pm 0.99\%$), while savanna and grassland formations were the most affected in relative area, with a reduction in vegetation cover of 27.43% $\pm 1.18\%$ and 19.04% $\pm 0.64\%$, respectively, between 1988 and 2018, mainly affecting the Cerrado, Pantanal, and Caatinga biomes^{35–38}. This can be explained by the negligence of the Brazilian state in monitoring deforestation in the country's non-forest formations, instituting the PRODES Cerrado only in 2016⁵, more than two decades after the beginning of PRODES Amazônia, the system responsible for monitor only forest formations in the Legal Amazon³⁹.

Specifically in the Legal Amazon, the period from 2008 to 2014 had the smallest deforested areas (see Supplementary Fig. S1a), which may be due to the soy moratorium, an agreement signed by large traders aiming at banning the purchase of production from areas deforested after 2006^{40,41}. Also noteworthy is the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon, developed in 2004, which sought to promote land and territorial planning, with an allocation of 25 Mha for the creation of new federal Conservation Units and 10 Mha for the demarcation of Indigenous Lands; similarly, monitoring and controlling deforestation through alert and surveillance systems resulted in a drop of about 60% in the annual rate of deforestation from 1996 to 2016^{42–44}. However, from 2012 onwards, our results indicate an increase in deforestation in forest formations in the Legal Amazon, which may be related to the beginning of a period of greater political, social, and economic instability in the country⁸.

In the Cerrado, deforestation did not follow the same downward trend (see Supplementary Fig. S1b). Between 2010 and 2013, the suppression of native areas in the biome surpassed the Legal Amazon, a fact that can be explained by less severe environmental restrictions, lack of monitoring systems and insufficient inspection actions^{29,45}, as well as the prevalence of expanding agricultural frontiers^{6,46,47}. In view of this favorable scenario for its occupation, in 2013 the biome surpassed the impressive mark of 50% of its territory anthropized⁵.

When analyzing the entire national territory, almost 35% are anthropized, and even though our data indicate a trend towards a reduction in deforestation, almost 10 Mha of pastures were abandoned and currently present a high presence of secondary vegetation. In the same period of analysis, we found that 9.64 Mha $\pm$ 0.45% of native vegetation were converted to crop, thus suggesting that better use of already open land could prevent the deforestation of new areas. In fact, the use of new management and production techniques are more efficient in terms of productivity than the expansion of new agricultural and livestock areas, thus avoiding underutilization and possible land abandonment⁴⁸. Likewise, and in addition to the preservation and restoration of native vegetation, practices such as more intensive and technified management, combined with the recovery of degraded pastures, can contribute to the preservation of the Brazilian biomes⁴⁹. Also noteworthy is the incorporation of low-carbon technologies (e.g. crop-livestock-forest integration; biological nitrogen fixation; no-till), providing an increase in crop productivity⁵⁰.

Methods

In this study we used a set of statistical analysis applied to point samples labeled with different Land Use and Land Cover (LULC) classes, derived from the visual interpretation of Landsat images obtained between 1985 and 2018, to produce unbiased and reliable area estimations for Brazil since 1985 (Figure 4). Seeking to provide a dataset adequate to generate independent analyzes, the sample design was developed considering random sampling stratified by the terrain slope and the topographic charts defined by the Brazilian Institute of Geography and Statistics-IBGE (⁵¹ - see Supplementary Fig. S2-3). The visual interpretation of the 85,152 samples (see Supplementary Fig. S4) considered a labeling criteria established for each LULC and Brazilian Biome and periodic training involving the team of interpreters. Using the final labeled samples, we produced area estimations, with the Horvitz-Thompson estimator, for 13 LULC classes (i.e. annual crops, forest formation, grasslands formation, other non-forest natural formations, others, pasture, perennial crops, savanna formation, semi-perennial crops, tree plantation, urban infrastructure, water, wetland), historical deforestation, and agricultural expansion for the entire national territory (according to six biomes) over 34 years (from 1985 to 2018).

Sampling Plan

The sampling planning was built looking for a parsimonious relationship between availability of human resources, time, reliability, and inferential precision. In the sampling design, the population (i.e. the total amount of 30x30m pixels needed to cover the entire Brazilian territory) was divided into domains/sub-populations defined by the grouping of four IBGE topographic charts⁵¹, named “grouped chart”, totaling 127 domains (see Supplementary Fig. S2). These domains were used as the smallest area for which a precision control of proportion estimates with confidence intervals was performed. For each grouped chart a proportional stratified probabilistic sampling of one stage was performed, where the stratification was defined by dividing the grouped chart into six slope classes adopted by the Brazilian Agricultural and Research Organization (EMBRAPA⁵²), and within each stratum a simple random sampling of the primary sampling units (i.e. pixels) was conducted.

The reliability and precision of the estimates were controlled in each grouped chart, in such a way that the sample size was dimensioned in order to guarantee a maximum margin of error of 5% and a confidence level of 95%. From this perspective, the maximum error expected for the entire national territory was 0.5%. Thus, and considering the inspection capacity, a minimum quantity of 500 points was defined for each grouped chart. In calculating the sample size, information on the variability and number of land cover and land use classes in each grouped chart was also taken into account, using as a reference the mapping done by Mapbiomas, referring to Collection 3 for the year 2015⁷ (see Supplementary Fig. S3). Thus, the sample size was established as an increasing function in relation to the number of classes and/or variability, in order to maintain the same level of confidence and margin of error. The variability information was derived from the maximum variance of the land use and land cover classes, and to consider the information on the number of classes, the Bonferroni correction⁵³ was applied, which adjusts the value of the quantile of the standard normal distribution.

Thus, the sample consisted of 85,152 points distributed throughout Brazil, which were drawn by simple random sampling in each grouped chart, resulting in 35,258 points for the Amazon biome, 21,290 for the Cerrado biome, 9,738 for the Caatinga biome, 14,497 for the Atlantic Forest biome, 2,008 for the Pantanal biome, and 2,361 for the Pampa biome (see Supplementary Fig. S4).

Reference Data and Software Infrastructure

The spatial unit of this study was a Landsat pixel, with a spatial resolution of 30m, and the main source of information for classification of land use and land cover was the historical collection of Landsat images, covering a period of 34 years (i.e. 1985 to 2018). The classification was generated through the visual interpretation of images obtained by the Landsat satellite series with less atmospheric interference (according to the CLOUD_COVER metadata) for the dry (i.e. June to October) and rainy (i.e. January to May) periods, using the NIR, SWIR1, RED false-color compositing. The interpretation took place via the Temporal Visual Inspection – TVI, an open source tool developed by the Image Processing and GIS Lab at the Federal University of Goiás (Lapig / UFG), which allows for greater flexibility in the analysis of sampling points with reference to historical series of satellite images (Figures S5-6).

Reference Labeling Protocol

The point samples were classified into 20 LULC classes, compatible with collection 3 of the MapBiomias project⁷ (see Supplementary Table S1), for which specific Landsat image interpretation criteria were established for each Brazilian biome (e.g. color, shades, texture, homogeneity, form, and context - accessible at: <https://lapig.iesa.ufg.br/chave/en/>), thus seeking to reduce the subjective aspects inherent to this process. Each sample was evaluated by three distinct interpreters, so that the final class was defined by a majority vote (i.e. the class with two or three votes). For samples with complete disagreement (i.e. assignment of three different classes), the final class was established a posteriori by a fourth supervisor-interpreter.

Area Estimation

For the area estimates in the study, forest, savanna, and grassland formations were considered as "Native Vegetation"; as "Agriculture" the annual, perennial, and semi-perennial crops; and as "others" the classes of rock outcrops, apicum, aquaculture, mangroves, mining, other non-vegetated areas, beaches, and dunes. After this grouping, the area estimates were calculated according to the reference value assigned to each pixel. For each class of interest, the *i*-th inspected pixel received the reference value, such that: if equals 1, it belongs to the class of interest, otherwise it is equal to 0. Then, an unbiased estimator of the proportion was used to calculate the area estimate of each class of LULC and LULC change. In order to assess whether the stratified sampling (SS) by relief and grouped chart produced a gain in the accuracy (of estimates of the proportions of the studied classes) in relation to a simple random sampling without replacement, we performed an analysis of the Sampling Plan Effect (SPE) based on the comparison of variances and standard errors of estimates (Figures S7-8).

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Data Availability

The final sampling dataset with all the classes, sampling probability, and weights is publicly available at <https://doi.org/10.5281/zenodo.5136666> under the Creative Commons License, which, despite its limitations, can contribute to several initiatives of LULC monitoring in Brazil. The TVI source code and the area estimator implementation are available at <https://github.com/lapig-ufg/tvi> and <https://github.com/lapig-ufg/tvi-analysis>, respectively, both under the MIT license.

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336 **Author contributions statement**

337 L.P., L.F., and A.M. conceived the idea of the study and, together with L.B., devised the methodological approach. A.M., E.S.,
338 V.M. and S.N. supervised the image interpretation work. A.M., V.M., L.P. and V.L. organized and processed the data and,
339 together with L.B. and L.F., analyzed the results. All the authors contributed to the discussions and writing or revision of the
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341 **Competing interests**

342 The author(s) declare no competing interests.

Figure 1. Annual area estimation for the land use and land cover classes greater than 15 Mha (a), and less than 15 Mha (b) for Brazil, between 1985 and 2018. The estimated standard error varied between 0.04% (perennial crops in 1986) and 0.37% (forest formation in 1985).

Figure 2. Estimated area for primary deforestation (i.e. first vegetation suppression event), using as baseline 1988, in the main vegetation formations of Brazil (a) and in the six Brazilian biomes (b - considering the new boundaries defined by⁵⁴).

Figure 3. Stable area of pasture and crop (i.e. without LULC-change between 1986 and 2018), and the cumulative area of crop expansion over native vegetation and pasture, pasture expansion over native vegetation, and secondary vegetation over pasture in (a) Brazil and in the six Brazilian biomes (b-g). For the estimates of native vegetation, all the vegetation formation (i.e. forest, savanna and grasslands) were considered.

Figure 4. Methodological approach used to design and label 85,152 point samples produced by this study. Based on it, we estimated areas for 13 LULC classes (e.g. Annual Crops, Forest Formation, Grasslands Formation, Pasture), historical deforestation and agriculture expansion (e.g. stable pasture, secondary vegetation over pasture, crop over native vegetation) for the entire national territory (according to six biomes) over 34 years (1985 until 2018).

Supplementary Files

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