Multitemporal analysis and mapping of land-use changes caused by sugarcane expansion in the state of São Paulo, southeast Brazil

Análise multitemporal e mapeamento das mudanças no uso da terra causadas pela expansão da cana-de-açúcar no estado de São Paulo, Sudeste do Brasil

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ABSTRACT

The change in land use and land cover caused by the expansion of sugar cane in a part of the State of São Paulo between 1988 and 2016 was mapped. The mapping was performedautomatically using orbital imagery from the Landsat Thematic Mapper (TM) satellite and manual delimitation of polygons. During

the period under study, sugarcane areas more than doubled, and expanded over 1.2 million hectares, mainly over pasture, annual crops and citrus. Faced with a shortage of land, the sugar energy sector must increase productivity, but in a sustainable way. To meet this challenge, in addition to increasing productivity per hectare, the sector must expand integrated agricultural practices and promote the conservation of native vegetation. Maps produced from large-scale classification of satellite image time series provide a more detailed understanding of land use dynamics and provide valuable input for land-use planning policies.

Keywords: Agricultural production. Conversion of areas. Geotechnologies. Territorial planning.

RESUMO

Mapeou-se a mudança de uso e cobertura da terra impulsionada pela expansão da cana-de-açúcar em parte do estado de São Paulo, entre 1988 e 2016. O mapeamento foi feito de forma automática usando imagens orbitais do satélite Landsat Thematic Mapper (TM) e delimitação de polígonos de forma manual. No período avaliado, as áreas de cana-de-açúcar mais que duplicaram e expandiram-se por 1,2 milhões de hectares, principalmente sobre áreas de pastagens, culturas anuais e citros. Diante da escassez de terras, o setor sucroenergético deve aumentar a produtividade, porém de forma sustentável. Para enfrentar esse desafio, além do ganho de produtividade por área, o setor deve ampliar as práticas agrícolas integradas e incentivar a preservação de vegetação nativa. Os mapas gerados a partir da classificação em larga escala de séries temporais de imagens de satélite proporcionam uma compreensão mais detalhada da dinâmica do uso da terra, além de oferecer subsídios valiosos para políticas de ordenamento territorial.

Palavras-chave: *Produção agrícola. Conversão de áreas. Geotecnologias. Planejamento territorial.*

1 INTRODUCTION

Brazil's historical experience in ethanol production began in 1975 with the establishment of the National Alcohol Program (ProÁlcool), which subsidised infrastructure and new technologies for large-scale production of sugarcane-based ethanol (Goldemberg, 2007; Zu Ermgassen *et al*., 2024). In addition, in the early 2000s, the use of ethanol was encouraged by the environmental attractiveness of non-fossil fuels and the introduction of biofuel engines in the market (Adami *et al*., 2012; Rudorff *et al*., 2010). Brazil is currently the world's largest producer of sugarcane ethanol. Its harvested area amounts to 8.6 million hectares and a total production of 28.5 billion litres of ethanol in the 2024/25 harvest season, and the state of São Paulo, its strongest producer, accounts for 4.3 million hectares (Conab, 2024). The incentive of the domestic market, combined with the environmental benefits of ethanol when compared to fossil fuels, has further stimulated the expansion of sugarcane cultivation in the already contested agrarian space of the Central-South region of Brazil.

In this sense, the complexity of the socioeconomic impacts of the expansion and intensification of sugarcane cultivation in this region of São Paulo has not yet been sufficiently illustrated and deserves to be highlighted, as this is the main sugarcane-producing region in Brazil. Important agroenvironmental planning mechanisms for the state of São Paulo have already been presented, such as the Sugarcane Agroecological Zoning and the Agri-Environmental Zoning for the Sugar and Alcohol Sector (Guarenghi *et al*., 2023), which are studies that favour a better organisation and adaptation for the expansion and occupation of land for sugarcane cultivation, in addition to subsidising the elaboration of public policies.

Considering that the expansion of sugarcane areas in São Paulo state's inland may increase, especially over other crops, and affect food production and land structure, there is an urgent need to assess the dynamics of land occupation and changes in land use at the regional level, to generate information

that can support the development of public policies and contribute to discipline the of future crop expansion. In this context, monitoring the expansion of sugarcane in the State of São Paulo becomes essential, and satellite remote sensing imagery has great technical potential for this type of analysis (Santos *et al*., 2022; Shimabukuro *et al*., 2023).

The northeastern region of São Paulo, which includes the Mogi-Guaçu and Pardo river basins, stands out in this dynamic context of changing land use and land cover due to agricultural crops, and shows that sugar and ethanol production are key components of rural development and energy strategies. The causes of land use and land-use change (LUC) are multiple, complex, interrelated, and changing over time. Therefore, predicting land-use change is uncertain because it is sensitive to many factors that can evolve in different directions, including crop productivity, internal and external prices of sugar and ethanol products, high labour costs, guarantee of monthly income from area rent, family succession, increase in regional land prices, among others (Barbosa *et al*., 2022; Ogura *et al*., 2022).

The increased demand for bioenergy sources will require more sustainable options in relation to changes in land use and occupation, aiming at reducing negative impacts such as the expansion of sugarcane cultivation in areas of native forest, areas featuring slopes greater than 12% and permanent preservation areas. Thus, this work had as its main objective to map, a period of about 30 years (1988 to 2016), the spatial-temporal dynamics of land cover and the changes in land-use, caused mainly by the expansion of sugarcane in a region of great importance for the economy of the State of São Paulo and Brazil, aiming to identify the land uses and the changes in land-use and cover and future trends.

2 MATERIAL AND METHODS

2.1 STUDY AREA

The study area comprises 125 municipalities located in the northeastern region of the State of São Paulo, and occupies 51.7 million hectares, or 20.5% of the State of São Paulo (Figure 1). This entire area was originally covered by vegetation of the Brazilian biomes Atlantic Forest and Cerrado. The region's climate is a transition of the Cwa climate type class according to the Köppen classification, and ranges from continental to upland, usually featuring two seasons characterised by the presence of two well-defined situations: rainy and hot in summer; and dry and cold in winter (Alvares *et al*., 2013).

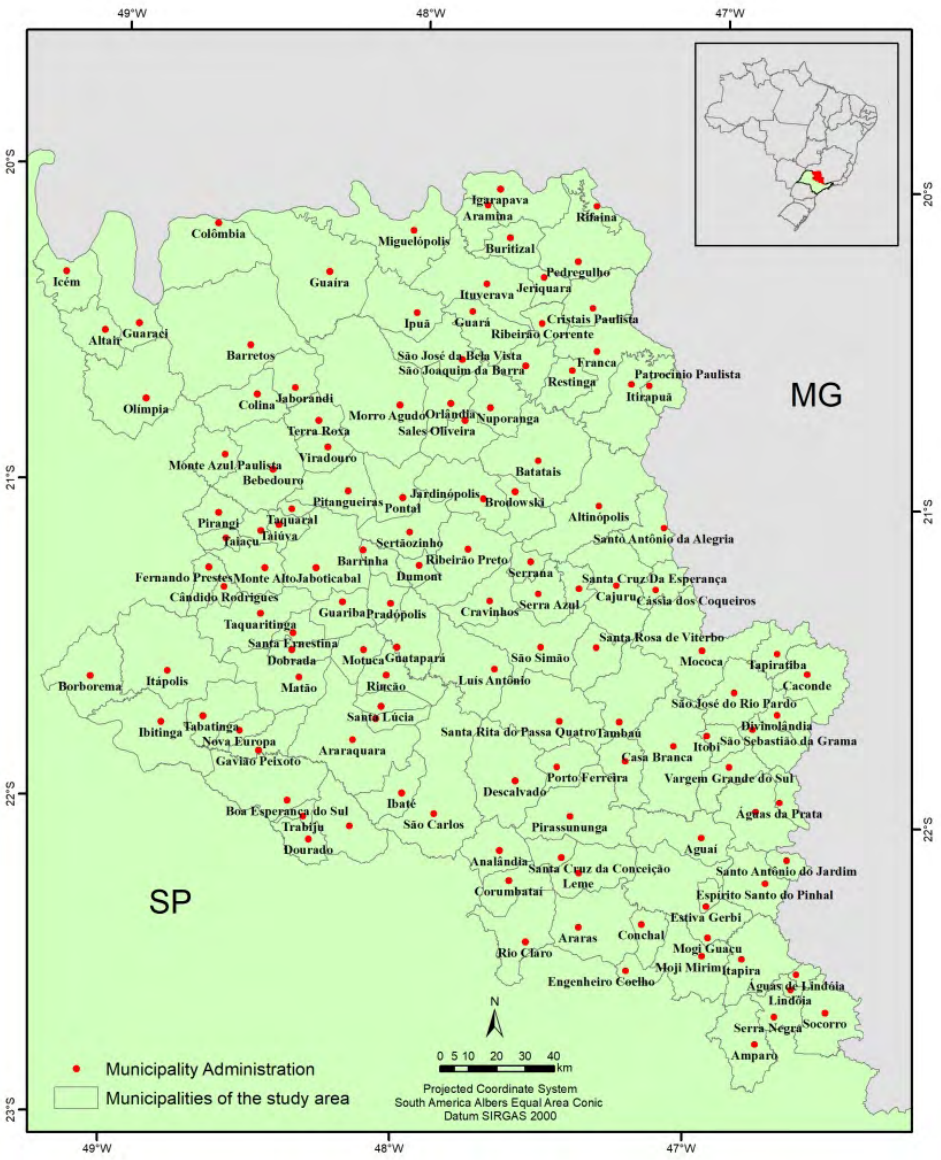


Figure 1 – Map showing the study area comprising 125 municipalities in the northeast region of the State of São Paulo

Source: Author's elaboration.

2.2 MAPPING METHODOLOGY

For the year 1988, mapping was performed using orbital images taken by Landsat 5 satellite's Thematic Mapper (TM) sensor, of bands RGB321 in the visible spectrum, with a spatial resolution of 30 m, of the following point orbits: 219/75, 219/76, 220/74, 220/75, 220/76, 221/74 and 221/75. The scene size covers an area of 170 x 185 km. After the images were inserted in a geoprocessing software and processed, the land-use classes were mapped on screen using the digitisation process.

In 2016, sugar cane areas were classified based on the update maps generated by the Canasat project (Rudorff *et al*., 2010). First this database of the 2010/2011 crop year was inserted into a Geographic Information System (GIS), the data were transformed to vector and added as a layer in the project. Subsequently, the sugar cane areas of the 2010 harvest were verified and updated for the year 2016 by means of visual on-screen interpretation of high-resolution images obtained from Google Earth Pro™.

In areas showing sugarcane permanence between 2010 and 2016, the polygons were maintained; in areas where sugarcane was replaced by another use in 2016, they were reclassified; finally, new areas identified in the 2016 mapping were included from the digitisation process, updating the sugarcane areas found in the municipalities of the Northeast region of the São Paulo State for the year 2016.

The images available on the free Google Earth™ platform present mosaics of scenes from different satellites, including those of medium spatial resolution, such as Landsat 8 OLI (Operational Land Imager), in the 30-m range, up to high spatial resolution satellites, such as the Spot 5 satellite, with a resolution of up to 1.5 m. In the same way, the platform offers access to the collection of Digital Globe, an American company that licenses satellite images, providing scenes from the Ikonos satellite (1.0 m resolution), Quickbird (0.60 m), GeoEye-1 (0.5 m), WorldView-2 and 3 (0.5 m), among others, making it an important tool for obtaining spatial information, although for certain locations the updating requires a more adequate time interval.

For the mapping of the other classes and areas occupied by pastures, annual crops, citrus, coffee, eucalyptus, rubber, native forest and urban areas, the image collection of the Google Earth™ platform was also used in a GIS environment. The same mapping method by on-screen visual interpretation and the same procedure used for sugarcane classification applied, but without the initial reference base. To resolve the doubts that arose after the visual interpretation, several field trips were carried out to verify the pre-classified areas, which conveyed a greater precision to the mapping of land use and cover and the study.

To assess the presence of sugarcane plantations in areas featuring steeper slopes, in another stage of this study, topographic data from the Topodata project, obtained from the geomorphometric database of Brazil, were used. This study worked with a digital elevation model and its local derivatives based on national coverage, applying data refinement methodologies and data resampling for the 30-m spatial resolution of the platform data, Shuttle Radar Topography Mission (SRTM), a spatial mission conducted by the North American Space Agency (Nasa).Thus, it was possible to spatially identify the locations where sugar cane plantations are concentrated in areas featuring slopes greater than 12%, which are likely to represent new land-use changes, such as pastures, planted forests or even the recovery of natural vegetation.

Coffee and pasture areas located above 800 m of altitude (hypsometric map) and featuring slopes of less than 20% (clinographic map), which represent areas with potential for coffee expansion, were also identified in the elaborated mapping and digital elevation model and its derived products, such as the slope class map.

Finally, the mapping of the areas irrigated using centralised irrigation systems (pivots) for the year 2016, in the municipalities of the Northeast region of the State of São Paulo, was also carried out through the identification and visual measurement of images on Google Earth™ platform, using mosaics of orbital scenes of medium and high spatial resolution.

3 RESULTS AND DISCUSSION

3.1 LAND-USE CHANGE FOR SUGARCANE CROP

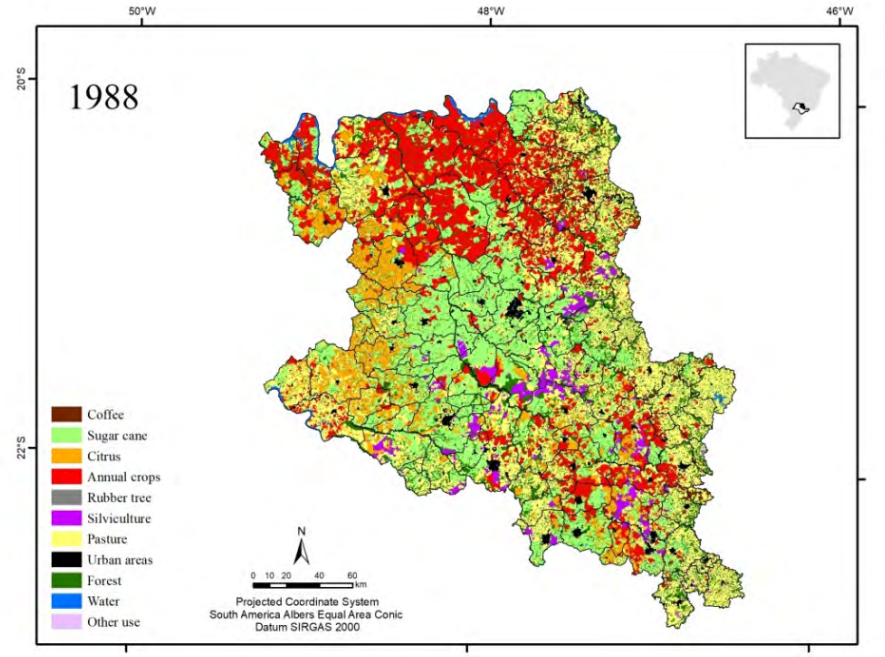
Sugarcane areas, which occupied approximately 1.086 million hectares (21%) in 1988, expanded to approximately 2.286 million hectares (44%) in 2016 (Table 1 and Figure 2), an increase of 23%. Our results show that during the period under study, the increase in sugarcane production did not occur in native forest areas, but mainly in pastures, which confirms results of several studies that also used satellite imagery (Adami *et al*., 2012; Alkimin *et al*., 2015; Guarenghi *et al*., 2023; Ogura *et al*., 2022; Rudorff *et al*., 2010; Spavorak *et al*., 2009).

Table 1 – Amount of land use (ha) and land-use change (ha) and percentage of total area (%) of sugarcane, pasture, annual crops, citrus, coffee, eucalyptus, rubber tree, native forest, built-up area and water bodies in the Northeast region of the State of São Paulo in 1988 and 2016

Land-Use (LU)	1988		2016	
	Area (ha)	Area (%)	*Area (ha)*	Area (%)
Sugarcane	1,085,996.4	21.0	2,286,349.6	44.2
Pasture	1,410,557.8	27.3	692,588.6	13.4
Annual crop	936,373.2	18.1	351,649.7	6.8
Citrus	486,168.2	9.4	301,527.9	5.8
Coffee	67,427,5	1.3	123,675.0	2.4
Eucalyptus	139.616.2	2.7	159,273.8	3.1
Rubber tree	16.7	0	4,106.3	0.1
Native forest	872,183.8	16.9	998,798.0	19.3
Urban area	90,562.8	1.8	166,355.9	3.2
Water	77,476.2	1.5	74,143.4	1.4
Other	4,257.6	0.1	12,167.9	0.3
Total	**5,170,636.1**	**100**	**5,170,636.1**	**100**

Source: Author's elaboration.

However, increased biofuel production may cause indirect land-use and land-cover change (iLUC) by displacing pasture or annual crops to other regions of the country when replaced by sugarcane (Zu Ermgassen *et al*., 2024). The income obtainedfrom the sale of land for planting sugar cane generally makes it possible to purchase larger areas in the north of Brazil, usually associated with deforestation for the openingof new pastures, this is the main indirect cause of the iLUC (Barretto *et al*., 2013; Parente; Ferreira, 2018; Sparovek *et al*., 2009).



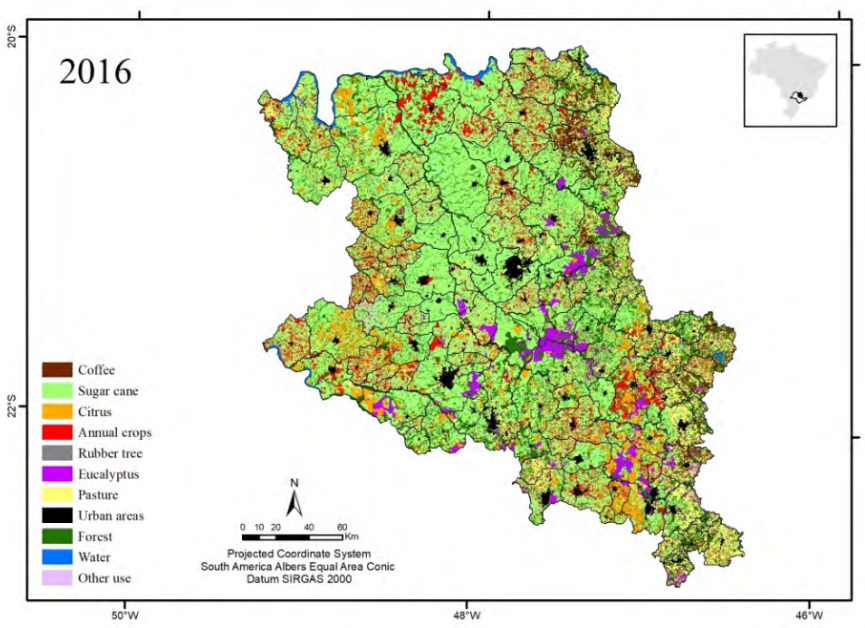


Figure 2 – Maps of Land-Use (LU) and Land-Use Change (LUC) in the Northeast of the São Paulo State, years 1988 and 2016

Source: Author's elaboration.

Assessing the impact of indirect land-use changes from biofuels in Brazil, Lapolla *et al*. (2010) showed that factors pushing the rangeland frontier into the Amazonian forests could especially offset the carbon savings from biofuels however, the magnitude of the iLUC caused is still uncertain and lacks more accurate detection methodologies (Zilberman, 2017).

According to some studies, the expansion of sugarcane can provide economic advantages for certain regions and municipalities, with the installation of agro-industries (Machado *et al*., 2017) which may lead to positive effects on socioeconomic development of municipalities, by influencing Gross Domestic Product (GDP) per capita, tax collection and increasing municipal income and population (Gilio; Moraes, 2016; Moraes *et al*., 2016; Neves *et al*., 2017).

Ther is also a favourable indicator for sugarcane in relation to food production. Every five years, on average, sugarcane fields must be renewed. Therefore, about 20% of the area can be occupied annually with other rotation crops, mainly soybeans and peanuts. The state of São Paulo grows peanuts in more than 90% of such reform areas (Miura *et al*., 2017), and stands out as the largest producer of oilseeds in Brazil. Thus, these spaces of renewal of sugarcane fields offer advantageous rotation alternatives.

Changes in land use, especially the increase in sugarcane production areas, may reflect on the prices of agricultural land. The expansion of grass cultivation, especially since 2002, was the main factor responsible for the increase in the price of agricultural land in São Paulo (Palludeto *et al*., 2018), it increased significantly again between 2007 and 2008; supported by investments made in ethanol production (Sauer; Leite, 2012).

Due to the implementation of the environmental protocol that prohibiting the burning of sugarcane in areas featuring slopes greater than 12% since 2017 (Silva *et al*., 2022), the possibility of allocatiing sugarcane lands for other crops or purposes increased in several municipalities, in a 'reverse' land-use change. Our results show that about 150 thousand hectares currently cultivated with sugarcane, in areas featuring slopes greater than 12% (7.1% of the area), may receive new crops, such as forests planted with eucalyptus or pastures, or be occupied by recovered native vegetation to increased the legal reserve required by law in rural properties (Figure 3).

Increasing productivity on the basis of sustainable development would be precisely the greatest challenge for the sugarcane and energy sectors in the region, where there are few areas left for crop expansion. This objective is urgent, considering that sugarcane has shown small increase in productivity since the late 1990s (Petrini *et al*., 2017). Currently, the sector is undergoing a regulation that approved the National Biofuels Policy, RenovaBio (Barbosa *et al*., 2022), which aims at the environmental responsibility of the sugar energy sector, the promotion and expansion of ethanol, the security of supply to the market, the generation of investments and new jobs, and additionally contributes to the reduction of greenhouse gas emissions, mainly through the substitution of fossil gasoline by renewable ethanol and the generation of renewable energy from bagasse and straw.

3.2. LAND-USE CHANGE FROM PASTURE TO SUGARCANE

Although pastures are still the main land use in the state of São Paulo, and occupy 39% of the state's area or 9.7 million hectares (Shimabukuro *et al*., 2023), the state has shown constant reduction of these areas, and the main driver of this process has been the rapid expansion of sugarcane cultivation (Guarenghi *et al*., 2023; Parente; Ferreira, 2018). In this study region, pastureland, which about 30 years ago accounted for the largest occupied area, about 1.5 million hectares (27% of the area of the region), occupied in 2016 about 700 thousand hectares, or 13% of the area of the whole region (Table 1 and Figure 2).

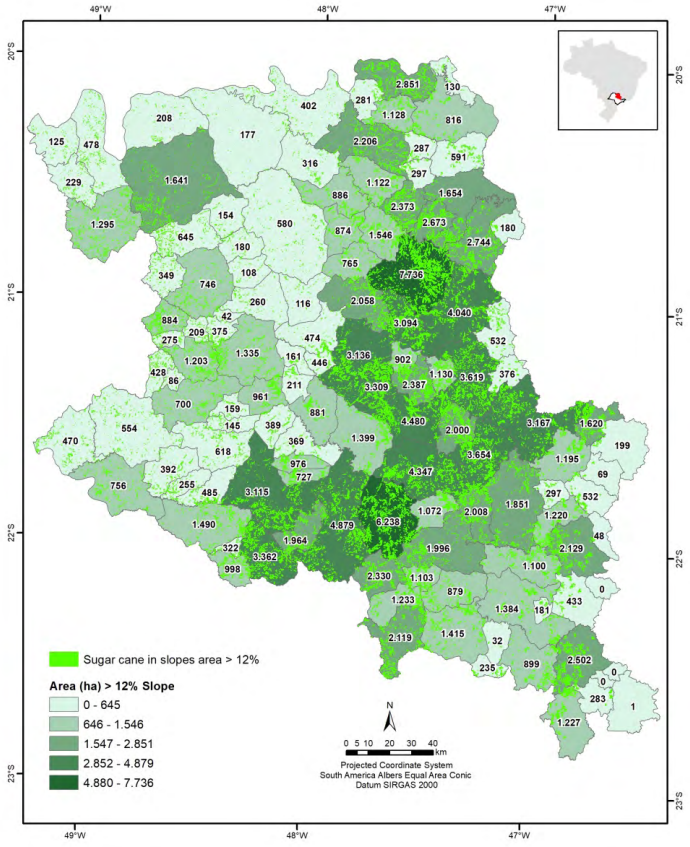


Figure 3 – Map of sugarcane areas for the year 2016, indicating the amount of area in hectares (ha) of each municipality featuring slope greater than 12% (green color)

Source: Author's elaboration.

Research results show that there are three possible alternatives for ranchers involved in milk production in the context of regional expansion of sugarcane areas: farmers resist the pressure of sugar-energy

agroindustries, coexist with sugarcane by leasing land and/or integrating sugarcane and milk production, and/or abandon the activity definitively (Egeskog *et al*., 2016; Novo *et al*., 2012; Petrini *et al*., 2017). Most ranchers are motivated to lease or sell their land due to high land prices in regions where sugarcane is expanding and to the attractive lease or purchase payments offered by the sugar energy sector.

Among the farmers who manage to stay on their land, most are small milk producers. An advantage that small farmers have over medium and large farmers is that they have family labor and can get rid of the high costs of hiring employees. This factor, combined with the adoption of technological changes in the field, animal genetics, pasture improvement, irrigation and milking process, can allow the generation of profits in small properties (Egeskog *et al*., 2016; Novo *et al*., 2016). Large meat producers are attracted to sell or lease their land and move their operations to more remote regions (Egeskog *et al*., 2016), where there is real possibility of expanding production and where land prices for beef production are lower.

3.3. LAND-USE CHANGE FROM ANNUAL CROPS

The area occupied by annual crops was reduced from 936,000 ha in 1988 to 352,000 ha in 2016 (Table 1 and Figure 2). In the study region, the expansion of sugarcane and the consequent reduction of annual cropland has been partially offset by investments in intensification of production through irrigation using central pivots, which enables harvesting three to four crops per year. However, in the northeastern part of the State of São Paulo, intensification through irrigation and productivity gains per hectare have not been able to compensate for the huge loss of land to sugarcane.

A total of 1,550 pivots responsible for the irrigation of 68,500 ha were recorded in the study area (Figure 4). The area irrigated by pivots is relevant, and accounts for 20% of the area planted with annual agricultural crops.

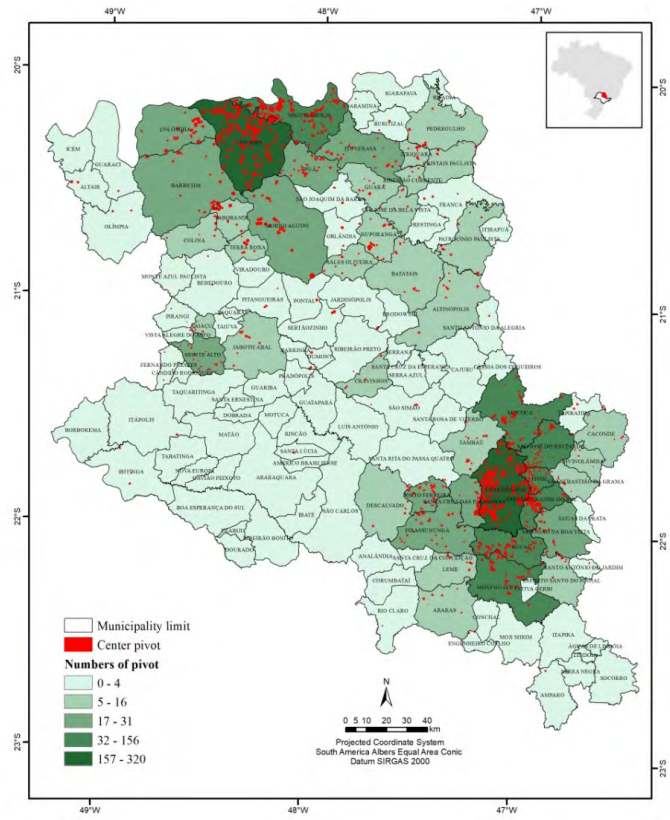


Figure 4 – Map of the study area showing in red the areas where central-pivot irrigation system is used

Source: Author's elaboration.

There is estimated potential to increase the irrigated area in the northeastern region of the State of São Paulo (Carvalho *et al*., 2020), to occupy areas currently planted with sugarcane. Irrigated areas can yield up to three productive cycles per year. Thus, irrigated cultivation of annual crops may be an alternative to make agricultural land more profitable and prevent the advance of sugar cane, or even recover part of the land already occupied by sugar cane.

3.4 LAND-USE CHANGE FROM CITRUS

The area dedicated to citrus cultivation in the region was reduced from 486,200 ha (9.4%) to 301,500 ha or 5.8% of the area during the studied periods (Table 1 and Figure 2). According to the census of citrus plantations of the state do São Paulo produced by the Fund for Citrus Protection – Fundecitrus (2024), the area of the Brazilian citrus belt, which includes municipalities in the States of São Paulo and Minas Gerais, is of 399,279 hectares. Therefore, the study area encompasses almost 75.4% of the area planted with citrus in the country and includes 75 municipalities (Figure 5).

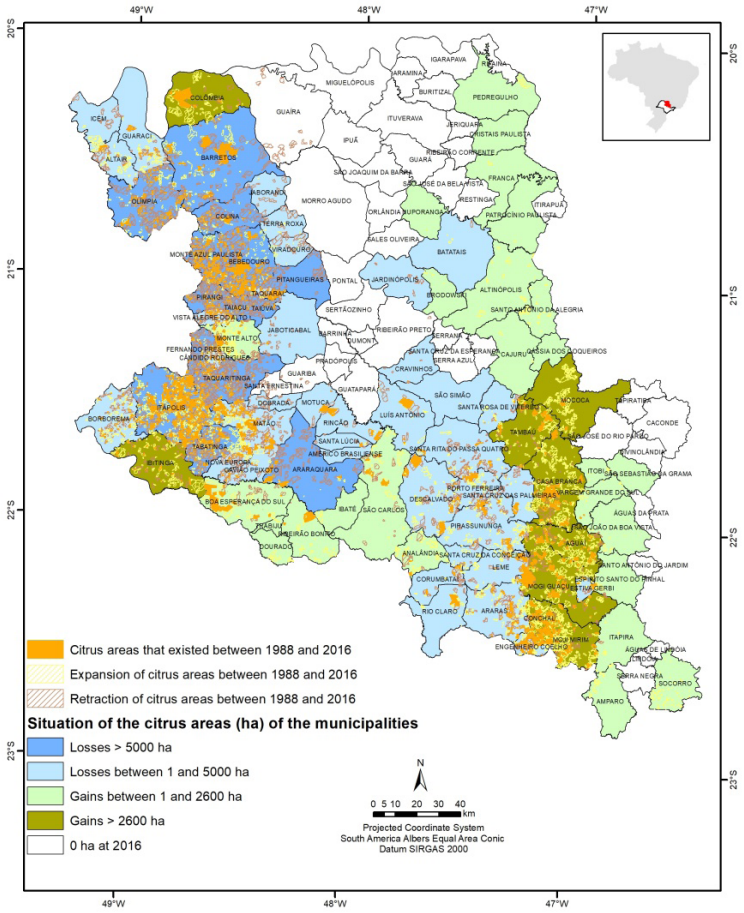


Figure 5 – Map showing the expansion and contraction of citrus areas in 1988 and 2016

Source: Author's elaboration.

Since 2008, citrus production has entered a period of transition, moving to a new economic cycle that faces major challenges: low farmer remuneration, increased production costs, phytosanitary problems and reduced international demand for orange juice (Neves *et al*., 2014). Labor is another item that has shown constant increase among the components of citrus production costs, mainly in the harvesting phase, which is still almost entirely done by hand (Amorim *et al*., 2018).

During the field visits, it was noted that many producers are leaving the citrus industry and migrating to the sugarcane industry, due to its greater economic competitiveness. However, it was observed that the eradication and abandonment of orchards has decreased in recent years, due to the renovation of orchards and the recovery of areas that were poorly managed or abandoned. A trend observed in the region is the concentration of citrus production in large estates, reducing the participation of small and medium enterprises.

In the citrus sector, only a few large farmers and industrial production areas remain. The increase in productivity seems to haves been particularly important to ensure the permanence of citrus growers in activity, as it mitigates the effects of high production costs (Amorim *et al*., 2018). According to the data analysed by Erpen *et al*. (2018), citrus production decreased by only 9.2% between 2001 and 2016, while the reduction in citrus area was of 29%. The higher yield can be attributed to the adoption of management techniques, mainly agricultural intensification through densification in new crops (Neves *et al*., 2014).

3.5 LAND-USE CHANGE FROM COFFEE

In contrast to the other agricultural crops evaluated, coffee cultivation in the region covered by this study has increased over the last 30 years. Between 1988 and 2016, the area dedicated to coffee crops increased by about 84%, from 67,000 hectares (1.3% of the region's area) to 123,000 hectares (2.4% of the region's area) (Table 1 and Figure 2). This fact contradicts the trend observed in most of the State of São Paulo, where sugarcane has gained space by competing with other crops and pastures (Adami *et al*., 2012; Guarenghi *et al*., 2023; Ogura *et al*., 2022; Rudorff *et al*., 2010).

The expansion of coffee areas has been concentrated in the eastern part of the study region, close to the border with the State of Minas Gerais, where edaphoclimatic conditions and climatic factors are more suitable for coffee cultivation. Nearly 103,600 hectares, or 90%, of the coffee areas of municipalities bordering the State of Minas Gerais, are located at altitudes higher than 800 m (Figure 6).

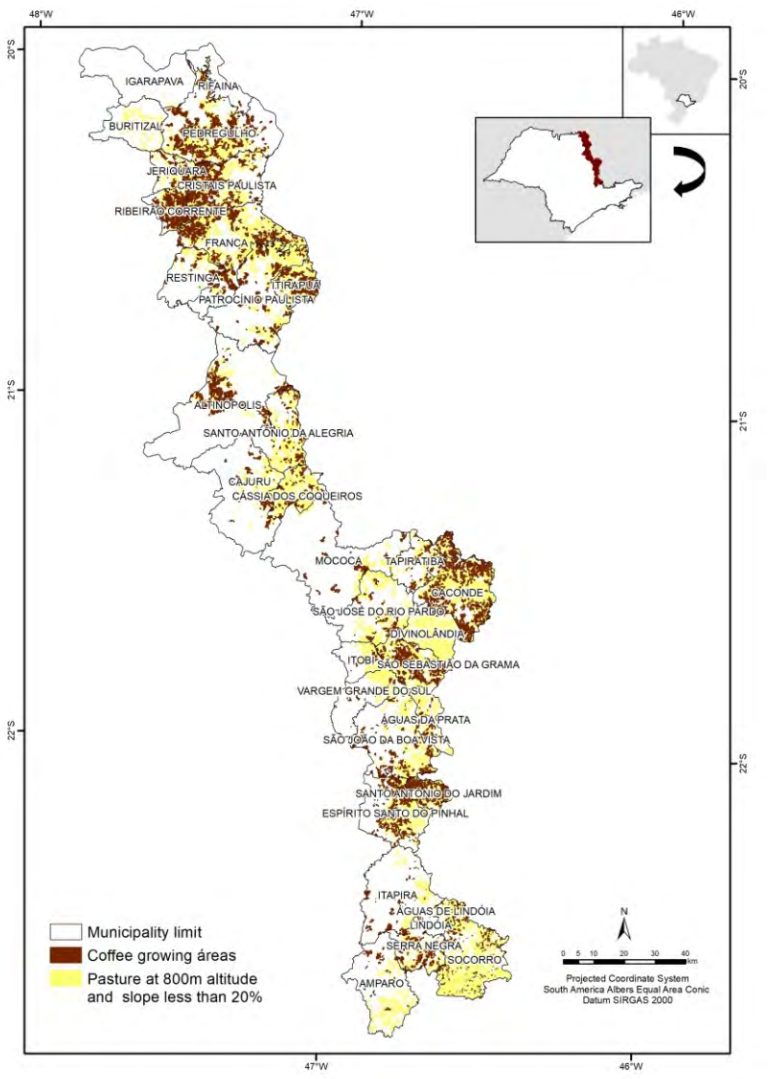


Figure 6 – Coffee and pasture lands located at heights above 800 m and featuringslopes of less than 20%, representing areas with potential for coffee expansion

Source: Author's elaboration.

Coffee plantations can still be found in most of the municipalities in the eastern part of the study region, as well as pastures, the type of land use that has ceded the most land in recent years. Of the total pasture area, 166,800 ha are located at altitudes higher than 800 m and featuring slopes of less than 20% (Figure 6). Thus, new expansions of coffee production could take place in areas featuring climate conditions and slopes that are favorable for mechanised harvesting.

3.6 LAND-USE CHANGE FROM PLANTATION FOREST (EUCALYPTUS, RUBBER TREE) AND NATIVE FOREST

In the northeastern region of São Paulo, the areas of cultivation of eucalyptus plantations increased from 140,000 hectares to 159,000 hectares during the studied period (Table 1 and Figure 2). The classification of forest plantations in the State of São Paulo counted 999 million hectares (IBA, 2023). This State contributes the most to the Brazilian economy, and has almost 18.1% of eucalyptus areas (Simabukuro *et al*., 2023). Its planted forests are considered not only an important source of income,

but also an alternative for the composition of permanent preservation areas, legal reserves and private natural heritage reserves (Ronquim *et al*., 2016). Almost all of the eucalyptus planted in the study area is for cellulose production by companies in the pulp and paper sector on their own or on leased land, and by the farmers who sell the production to these companies themselves.

Eucalyptus may be considered an alternative crop for areas featuring steeper slopes, which are not suitable for mechanised agricultural cultivation, and may possibly occupy areas made available for sugar cane cultivation on lands featuring slopes greater than 12%. Mechanisation of eucalyptus cultivation currently allows planting and harvesting on extremely steep terrain and makes it economically viable. Figure 7 shows that the main expansions of eucalyptus plantations are in municipalities characterised by lands featuringsteep slopes, located in the eastern part of São Paulo on the border with the state of Minas Gerais.

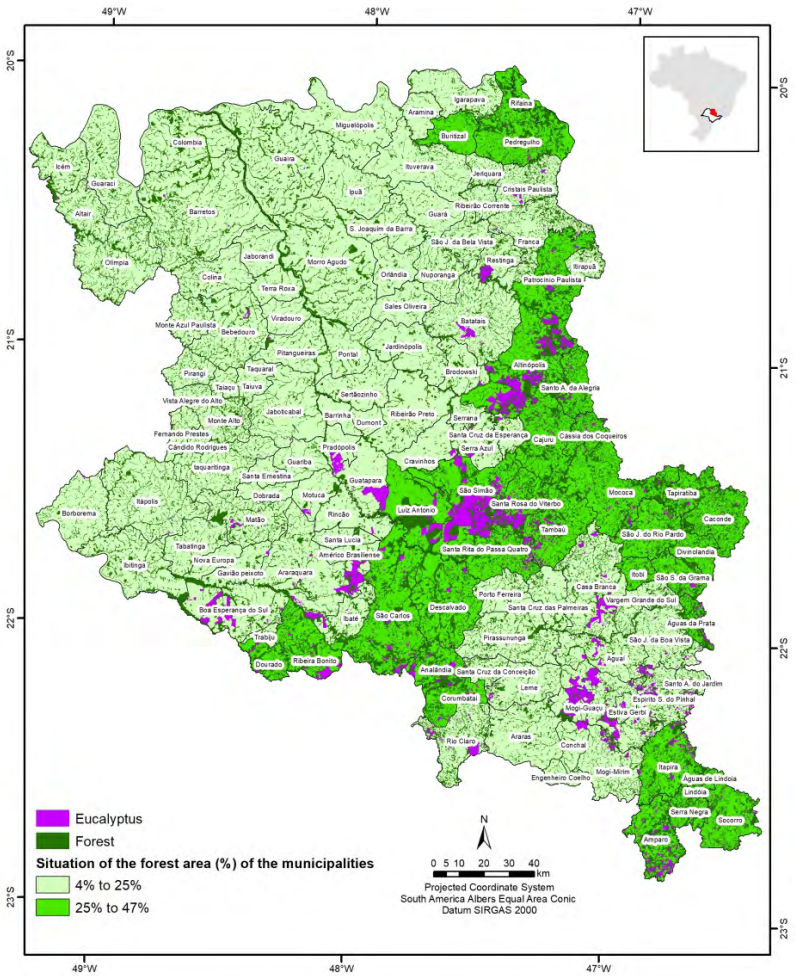


Figure 7 – Mapping of native forest, eucalyptus, and municipalities sowing the highest percentage of native forest areas

Source: Author's elaboration.

The simultaneous increase in eucalyptus and sugarcane areas (Table 1) show that these two monocultures do not compete in terms of area, but occupy land that has mainly served for pastures, annual crops and citrus. The growth of these two agribusinesses is driven by other businesses that have economic and financial structures that favour both the acquisition and lease of new land areas and business sustainability, which is different from crops that are generally maintained mostly by farmers.

Areas of rubber in the study region haves increased from 192 hectares to about 4,000 hectares. However, the total exploration area is currently insignificant in view of the 51.7 million hectares of the 125 municipalities analysed here (Table 1 and Figure 2). The increase is mainly in citrus and degraded pastures. The State of São Paulo is the largest producer of natural rubber in the country, dedicating about 134.2 thousand hectares to rubber cultivation (Oliveira; Gonçalves, 2024). The conditions of the northern portion of the study region are ideal for rubber cultivation, because of the favorable annual rainfall rate and temperature.

The clearing of land for new agricultural crops and livestock has contributed to the destruction of native flora in the state of São Paulo since the 19th century. The use of numerous controlled burns to clear forests and make way for pastures has impeded forest regeneration and contributed to the establishment of an anthropic landscape that currently dominates a significant portion of the state's land (Guarenghi *et al*., 2023; Rudorff *et al*., 2010). Currently, native forest areas in the State of São Paulo are mainly concentrated in the eastern region, mostly on steeper slopes, and account for 4.7 million hectares or 19% of the state's area (Shimabukuro *et al*., 2023).

The native forest areas in the study region accounted for 20% in 2016, against 17% in 1988, an increase of about 126 thousand hectares (Table 1 and Figure 2). These 998.798,0 hectares are only smaller than areas of sugar cane. There are many areas of regenerating native forest vegetation, mainly at the edges of forest fragments. Few forests in the region are characterised as primary, with the exception of State Protected Areas (Ronquim *et al*., 2024).

The increase in forested areas was not due to planting, but to spontaneous regeneration as a result of abandonment. The regeneration of native vegetation was also due to the greater care for Permanent Preservation Areas (APP) near the courses of rivers that cross agricultural properties. Native forest areas increased mainly in municipalities characterised by sloping terrain, mostly located on the border with the State of Minas Gerais (Figure 7). Under these conditions of great declivity, these areas are less suitable for agriculture and become, abandoned or poorly managed, and the native vegetation returns over the years. This phenomenon of natural regeneration has also been observed in the São Paulo part of the Paraíba do Sul river basin (Bicudo *et al*., 2023; Ronquim *et al*., 2024).

4 CONCLUSIONS

The main change in land use and cover during the study period was the expansion of sugarcane fields, which occupied about 1,086 million hectares in the region in 1988 (21%) and expanded to about 2,286 million hectares (44%) in 2016, an increase of 23%. The main challenge for the sugar-energy sector in the study region is to increase productivity in a sustainable manner, as new areas for expansion are scarce.

Livestock, which is the largest use in the region, has by far lost the most land. It now occupies 13% of the area of the whole region. The producers who remained in the activity underwent a selection process, in which the most technical ones remained and adopted economies of scale or opted for intensification.

Annual crops, mainly cereals, were reduced to almost a third of what they were in 1988. Some of the cereal producers have invested in production intensification, through irrigated cultivation using central pivots, to yield three to four crops per year.

Citrus plantations in the region have decreased over time, and this citrus park is threatened by a very serious phytosanitary factor, the incidence of Huanglongbing disease (HLB), or greening. The yield per hectare has been maintained due to the agricultural intensification or densification in new plantations, which increases the production per hectare.

Coffee plantations lost land to sugar cane in a large part of the region's municipalities, but in thiscentury, the area of coffee plantations increased again to, reach 80% more than in 1988. Coffee crops are concentrated in the east portion of the state of São Paulo, near the border with Minas Gerais, a microregion showing favorable conditions for the production of quality coffee. The intensification of coffee production is mainly due to the increase in the number of plants per hectare and the use of mechanised harvesting. In east São Paulo, coffee cultivation can expand and concentrate even more.

Eucalyptus and native vegetation areas haves increased significantly in the region. In the coming years, a new increase is expected in these native vegetation areas, due to the transition of areas unsuitable for agriculture and to an increase in Legal Reserve and Permanent Preservation Areas, in view of the greater pressure caused by the new Forest Code. Despite the natural increase in native vegetation area, the sugar energy sector must expand and promote the preservation and reforestation of native vegetation.

Despite the difficulties of mapping land-use and occupation using satellite imagery on small areas and permanent crops showing similar spectral responses. The maps and data produced by geographic information systems have proven to be important tools for understanding, analyzing and planning the spatio-temporal dynamics of land use and land-cover change at the regional level, providing technical support to decision-makers and for the formulation of public policies that discipline the expansion of land use in order to guide agricultural production and land use and occupation in an organised and sustainable manner. New methodologies must be developed for the automatic determination of land use and occupation in small areas.

The development of public policies for the agricultural sector in the State of São Paulo must consider land occupation issues as important factor in the variation of food production. It is necessary to develop public policies that seek greater investment in agricultural research to increase the production of food products, as well as to subsidize producers, so that they remain on their land and produce food crops in a sustainable way, ensuring a safe level of supply and prices for food.

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