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Article

Pedological Aspects of the Sugarcane-Ethanol Expansion in Southwestern Goiás

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ABSTRACT
The Brazilian Cerrado has undergone changes in land use driven by the expansion of the sugar-energy sector, linked to the National Agroenergy Plan. The objective of this study was to understand this expansion dynamic through edaphic (soil-related) and anthropic factors in the southwestern region of Goiás. The methodology of this research used Remote Sensing and Geoprocessing techniques, which included: mapping land use, with a focus on sugarcane in a temporal sequence for the years 1985, 1995, 2005, 2010, 2016, and 2019; mapping the Agricultural Suitability of Land Use in the region; vectorizing of logistical systems for ethanol distribution planned and implemented in southwestern Goiás and its bordering areas; and geospatial analysis of this process, integrating the dynamics of sugarcane expansion with the physical environment and infrastructure. The results of this study showed that the changes in land use driven by sugarcane initially relied on natural pedological conditions as the main production factor. Subsequently, technological systems for production distribution focusing on low-cost transportation were utilized, forming the pedo-logistic composition of sugarcane, marking a new phase of agricultural modernization in the region
Keywords: land use changes; agricultural suitability of land use; technology; production cells

RESUMO
O Cerrado brasileiro passou pelo processo de mudanças de uso dos solos promovido pela expansão sucroenergética, associado ao Plano Nacional de Agroenergia. O objetivo deste estudo foi compreender esta dinâmica de expansão por meio dos fatores edáficos e antrópicos na região do Sudoeste goiano. A metodologia desta pesquisa utilizou técnicas de Sensoriamento Remoto e de Geoprocessamento, que consistiram no mapeamento do uso do solo, com destaque à cana-de-açúcar em uma sucessão temporal para os anos de 1985, 1995, 2005, 2010, 2016 e 2019; no mapeamento Aptidão Agrícola do Uso das Terras da região; a vetorização dos sistemas logísticos de escoamento do etanol planejados e implementados no Sudoeste de Goiás e em suas áreas lindeiras; a análise geoespacial deste processo, integrando a dinâmica da expansão sucroalcooleira com o meio físico e a infraestrutura. Os resultados deste estudo mostraram que as mudanças de uso do solo, promovidas pela cana-de-açúcar, empregaram inicialmente condições pedológicas naturais, como principal fator de produção, posteriormente, faz-se uso do aparelhamento tecnológico de escoamento de produção focados no transporte de baixo custo, formando a composição pedologística da cana-de-açúcar que se configurou em uma nova etapa da modernização da agricultura regional.
Palavras-chave: mudanças de uso do solo; aptidão agrícola do uso das terras; tecnologia; células de produção.

Introduction

The world's growing demand for new energy sources, linked to the global environmental crisis, has led to an intense search for new sustainable energy matrices compared to oil derivatives. Ethanol from sugar cane has gained great international prominence for being an important substitute for fossil fuels with less polluting potential (Unica, 2008).

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Brazil has gained prominence as the largest producer of sugarcane ethanol in the world, using this energy technology on a large scale in the national vehicle fleet since the 1970s. The use of biofuels as an alternative to oil was driven by the instability of the international fuel market crises, which led to an intense rise in prices. Since then, the country has seen an increase in its sugarcane production areas, especially since the 2000s, when there was an increase in global demand for more sustainable renewable fuels, placing Brazil at the forefront of the global scenario (Gomes & Fernandes, 2014). During this same period, the Brazilian car market began to adopt dual-fuel engines, powered by ethanol as well as gasoline, increasing demand in the domestic market (Pietrafesa et al. 2016).

Since the beginning of the implementation of Brazilian ethanol as a substitute fuel for gasoline, the sector has developed new technologies that have modernized the country's sugar and alcohol production. These advances have occurred concurrently with the implementation of new public environmental policies, related to the National Agroenergy Plan, which have brought about a third-generation biofuel production model with greater use of waste and greater territorial control of production (Bittencourt & Gomes 2014; Gomes & Fernandes 2014; Manzatto et al. 2009).

In this context, the Brazilian sugar-alcohol sector was initially structured around two regional axes, the first consolidated in the Northeast and the second in the Southeast of the country. The intensification of this expansion promoted the migration of these axes to the areas of the Brazilian Cerrado, especially the state of Goiás, specifically the Southwest of Goiás, a region where the frontier of intensive agriculture is advancing (Trindade, 2015).

The sugar-energy expansion model in southwestern Goiás is based on the technological overlap of crops with a lower level of technology *per capita*. The sugarcane sector promotes the replacement of grain areas, pastures and native vegetation, induced by pedological conditions, above all, the agricultural suitability of land use that influences the production of sugarcane per hectare and the logistical factors of transport, implemented through public investments that manage to minimize the economic impacts of transporting production (Barbalho *et al.* 2013; Castilho 2015).

The Cerrado areas of southwestern Goiás have achieved sugar-energy production within the framework of the proposed relationship between the relevant factors and the soils and the flow of biofuels to the major commercial centers. The aim of this study is to understand the dynamics of sugar-energy expansion in this region through edaphic and anthropic factors. This process will be approached through an understanding of sugarcane expansion in the region, proposing the intrinsic relationship of the spatial dynamics of ethanol production within the influence of land use suitability factors and the planning and implementation of logistics modes.

Materials and Methods

The development of this research is based on four stages, which consist of a discussion of sugar-energy expansion in southwestern Goiás, presenting the dynamics of sugarcane and the main land-use classes present in the region; then we discuss the influence of the agricultural suitability of land use on the expansion model during the National Alcohol Program (PROÁLCOOL) and the National Agroenergy Plan (PNA), from the perspective of the search for better soils; the third part analyzes the influence of logistics systems on the spatial structure of the sector in the region; finally, an integrated analysis of the multi-temporal behavior of the sugar-energy cells in the southwest of Goiás is carried out (Figure 1).

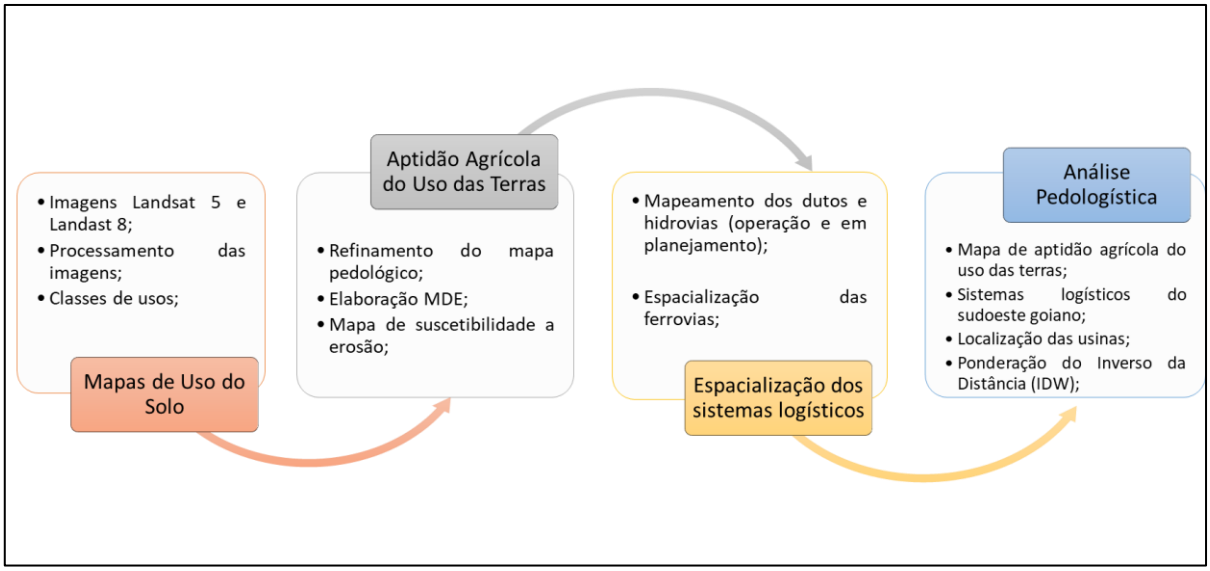

Figure 1- Methodological procedures of the research. Organizer: the author (2021).

The first stage of the research consisted of drawing up land use maps of the Southwest Goiano region, highlighting the classes of use referring to agriculture, pasture, sugar cane, vegetation, bodies of water or drainage and urban areas. The land use maps were developed using remote sensing and geoprocessing techniques, using images from the Landsat 5 satellite, which covered the years 1985, 1995, 2005, 2010, and the Landsat 8 satellite, which covered the years 2013, 2016 and 2019, respectively with scenes 224/72, 223/72,222/72, 224/73,223/73, 222/73. These images were used for*:* a) color composition in bands R (3), G(4), B(5); b) geometric correction (georeferencing) of the Landsat 5 images, based on the Landsat 8 images; c) segmentation by similarity and supervised classification by regions that grouped the areas based on the spectral response of the groups of similar pixels that generated data in *Raster* format; d) conversion of these data to *Shapefile* format, classifying it based on the interpretation of the groups of polygons, at a scale of 1:50,000 scale, analyzing the sugarcane areas based on photo interpretation of the spectral response of the targets, considering the pattern of shapes, color, tone, geometry and texture. These steps were carried out using Envi

5.1, Spring 5.4.3 and Arcgis 10.3 software, from which the areas of the selected use classes were calculated, generating tables in hectares that were worked on in Excel and representing changes in land use using the Sankey Diagram (Pimentel et al. 2011; Trindade 2015; Duarte & Silva 2019).

The second stage of the research consisted of analyzing sugar-energy expansion in relation to the agricultural suitability of land use in southwest Goiás. At this stage, the agricultural suitability map was developed based on the methodology of Ramalho Filho & Beek (1995), which considers the determination of the cartographic representation of the methods of handling the land in relation to the physical/chemical attributes of the soils, related to the factors limiting use, comprising fertility deficiency, water deficiency, excess water or oxygen deficiency, susceptibility to erosion and impediments to mechanization.

To do this, Arcgis 10.3 software was used to develop the pedological map of Southwestern Goiás using the technique of refining the soil cartographic bases of Embrapa Solos and the State Geoinformation System (SIEG) to a scale of 1:100,000, classifying them at the third categorical level, as developed by Trindade (2015). The slope map was drawn up by obtaining the Digital Model of Elevation of the Topodata images, with intervals of 0-6%; 6-12%; 12-20%, 20-45% and >45% (Bertoni & Lombardi Neto 1985; Ramalho Filho & Beek 1995).

Next, the laminar erosion susceptibility map was drawn up, which classified the erosive potential of the region into the following classes: not very susceptible, not very susceptible, moderately susceptible, very susceptible and extremely susceptible to erosion (Bertoni; Lombardi Neto, 1985). Lastly, a map of conservation areas was drawn up, which consisted of mapping the Permanent Protection Areas (PPAs) and Conservation Units in the southwest of Goiás (Barbalho et al. 2013).

The Agricultural Land Use Suitability map was drawn up based on the environmental maps of the physical environment, which considered the following factors, according to Ramalho Filho & Beek (1995): 1) the management levels, classified as management level A (primitive) with agricultural practices at a low technical level; management level B (poorly developed) with an average level of technology; and management level C (developed), related to intense use of technology; 2) the agricultural suitability groups which correspond to numbers 1 to 6, with 1, 2 and 3 relating to the crop group, according to their level of management; 4, 5 and 6 corresponding to the use of planted pastures, forestry and/or natural pastures and areas intended for the preservation of fauna and flora, as shown in Table 1:

Chart 1: Symbology corresponding to the land's agricultural suitability classes.

Agricultural suitability classes	Types of Use					
	Farming			Planted Pasture	Forestry	Natural Pasture
	Management Level A, B, C			Management Level B	Management Level C	Management Level A
Good	A	B	C	P	S	N
Regular	A	b	c	p	s	n
Restricted	(a)	(b)	(c)	(p)	(s)	(n)
Unfit	-	-	-	-	-	-

Source: Ramalho Filho & Beek (1995)

Considering the methodological model adopted, the agricultural suitability classes in the southwest of Goiás were classified according to their groups, types of use and level of management, as shown in Table 1.

These data w analyzed together with the expansion of sugarcane plantations, from 1985 to 2019, and also considered the technological relationship (for crops) with the management groups in the previous table, classified as class 1 (Intense Technological Use), class 2 (Medium Technological Use), class 3 (Low Technological Use), class 4 and 5 (Restricted) and class 6 (Conservation).

The third stage of this research was based on the spatialization of the logistics systems that have been set up and are being planned for the exclusive use of ethanol and other types. This stage aimed to draw up the routes of the Multimodal Ethanol Transport System and the rail routes influencing the southwest of Goiás, the North-South Railway and the North Railway. The first system was developed by creating *shapefile* files with the pipeline and waterway routes proposed by the Logum Public-Private Consortium (2020). This stage included the creation of the vectors of the pipelines and waterways, in operation and in planning, presented by the consortium covering the Center-South region. The route data for this multimodal system were developed using Arcgis 10.3 software with the aid of Landsat 8 satellite images.

Table 1: Classification of the agricultural suitability of land use in Southwestern Goiás.

Group	Use	APT class	Caption
1	Washed ras	1 ABC	Land belonging to the good crop suitability class at management levels A, B and C.
		1 ABc	Land belonging to the suitability class good for crops at management levels A and B and fair at level C.
		1 bC	Land belonging to the suitability class good for crops at management level C, regular at level B and unsuitable at level A.
		1 A(b)	Land belonging to the suitability class good for crops at management level A, restricted at management level B and unsuitable at level C.
2		2 bc	Land belonging to the medium suitability class for crops at management level B and C, unsuitable at management level A.
		2 ab(c)	Land with medium suitability for crops at management levels A and B, restricted to management level C.
		2 ab	Land with medium suitability for crops at management levels A and B and unsuitable at management level C.
		2 a(b)	Land with medium suitability for crops at management level A, restricted at management level B and unsuitable at management level A.
		2 (ab)	Land with regular suitability for crops at management levels A and B, unsuitable for management level C.
3		3 (ab)	Land with restricted suitability for crops at management levels A and B, and unsuitable at management level C.
4	Folder gem Floor plan	4p	Land belonging to the medium suitability class for planted pastures.
		4 (p)	Land belonging to the restricted suitability class for planted pastures.
5	Folder gem Natu ral and/or Silvi culture ra	5 s	Middle-class land for forestry.
		5 (s)	Land belonging to the restricted forestry class.
		5 sn	Land belonging to the middle class for forestry and natural pasture.
		5 (sn)	Land belonging to the restricted class for forestry and natural pasture
6	Restri Usage Options	6	Land unsuitable for agricultural use and environmentally restricted.

Source: Source: the author (2021).

The second logistical system present in southwest Goiás, with potential for biofuel transportation, is the railway. The layouts of these systems were compiled using files from the National Land Transport Agency (ANTT), which were corrected using Landsat 8 satellite images. With the two logistics modes structured, the areas of sugar-energy expansion in the study region were analyzed.

The last stage of this research consisted of analyzing data on the agricultural suitability of land uses, the multimodal logistics systems present in the region and the spatial distribution of sugar-alcohol plants in Southwestern Goiás from 1985 to 2019, referred to in this study as Pedological Composition. This stage began with defining the municipalities where the processing plants were located in southwest Goiás, which totaled 14 (fourteen) municipalities with plants in operation during the period studied.

This data was analyzed using the geostatistical tool Interpolation by Inverse Distance Weighting (IDW), available in Arcgis 10.3, following the algorithm: *Spatial Analyst Tools-Interpolation-IDW* and taking as *input* the ratio of the number of mills/municipality. The results were classified according to their concentration, forming agro-energy production cells. Based on the creation of these production cells, the influence of pedological aptitude and/or logistical factors on the expansion of plants in the study area was determined.

Results and Discussions

The sugar-energy boom in Southwestern Goiás

Sudoeste Goiano is located in the state of Goiás in the Center-West of Brazil in a Cerrado area. In recent years, the study region has seen an increase in the number of mills spread over three important periods: from 1946 to 1986, with three (03) mills; from 2003 to 2009, with a further eight (08) mills; and from 2012 to the current period, with a further five (05) mills, totaling sixteen (16) production units (Figure 2).

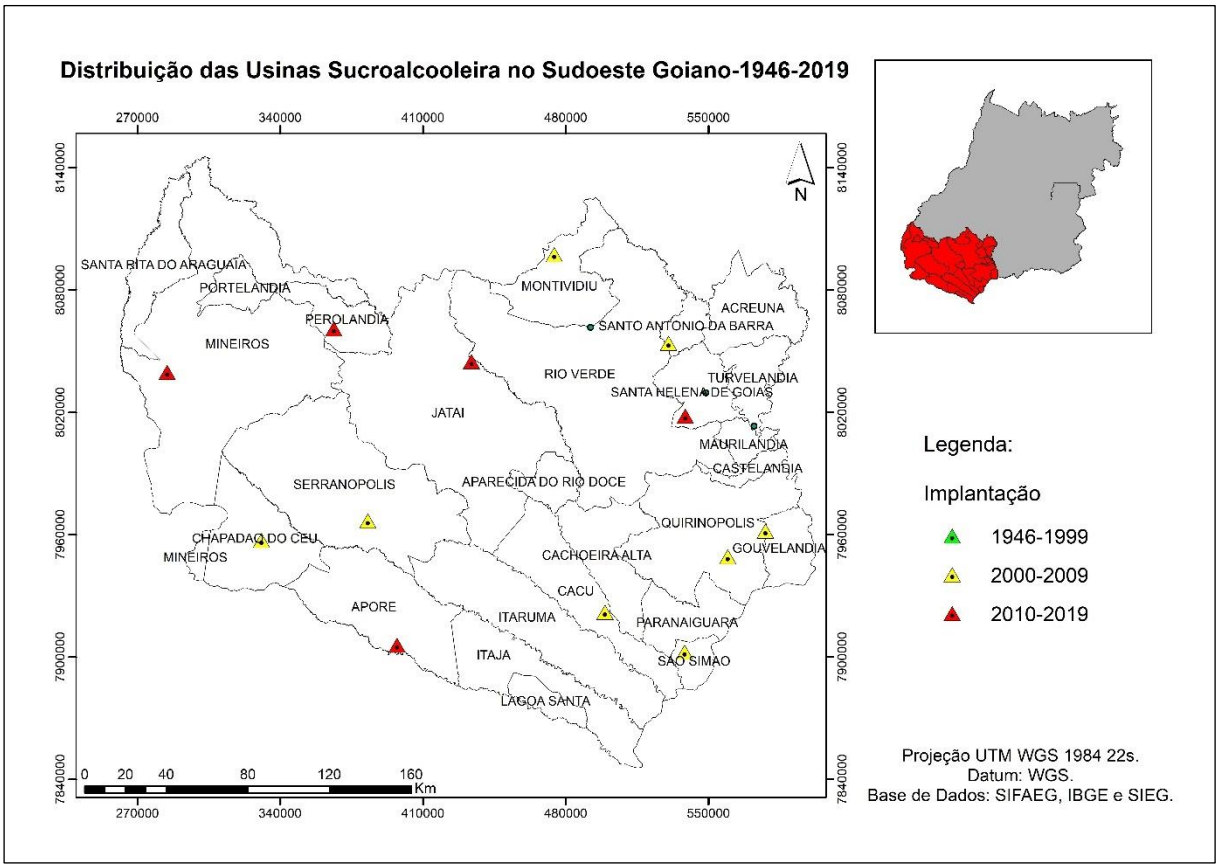

Figure 2- Progress of sugar and alcohol plants in the Southwest Goiano Planning Region. Source: SIFAEG, SIEG (2021).

The results obtained by the research point to spatial changes over the last four decades in relation to the advance of sugar-energy production in the Southwestern region of Goiás, associated with the increase in the number of mills and the areas planted with sugarcane. The periods analyzed correspond to 1985, 1995, 2005, 2010, 2013, 2016 and 2019. This time frame includes two important phases in the expansion of ethanol production in Brazil and also in the southwest of Goiás: the period related to PROÁLCOOL (1975 to 1990) and the National Agroenergy Plan (PNA), corresponding to the recent expansion that began in 2000 until the present day.

The multi-temporal analysis of land use showed the changes in the agricultural and natural landscape of the Cerrado areas, highlighting the main advances and retreats of agricultural production areas, considering the classes of use that have been influenced by the expansion of sugar-energy, represented by agriculture (grain crops), sugarcane (areas related to the agro-energy sector), pastures (cattle production areas), vegetation (native Cerrado areas), drainage (drainage areas in general) and urban areas (Figure 3).

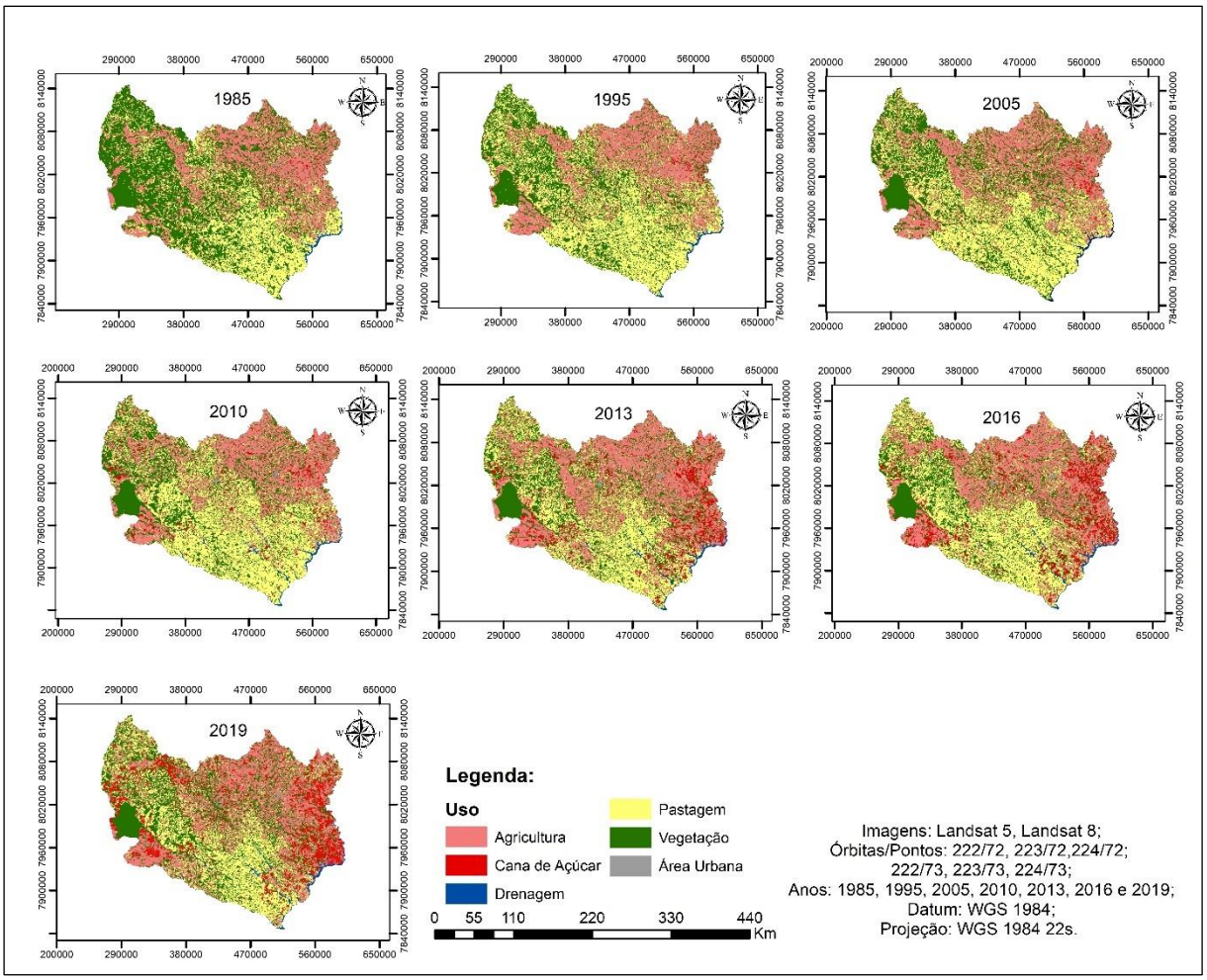

Figure 3 - Land use in Southwestern Goiás from 1985 to 2019. Source: the author (2021). Source: the author (2021).

The land use classes selected in this study have changed in the light of the relationship between the economic and natural matrices, as can be seen in the data in Table 2.

Table 2 - Land use in southwestern Goiás - 1985 to 2019 (Hectares).

Land Use	1985	1995	2005	2010	2013	2016	2019
Agriculture	1.835.555,15	1.812.589,49	2.040.221,72	1.951.659,00	2.460.597,17	2.180.902,54	2.090.1
Pasture	1.664.491,28	2.261.631,78	2.045.402,40	2.260.286,49	1.659.564,66	1.853.001,97	1.523.5
Vegetation	2.594.061,05	1.997.667,04	1.954.333,47	1.713.394,99	1.606.437,98	1.574.223,31	1.863.5
Sugarcane	7.677,88	25.356,45	50.838,37	143.729,53	340.832,82	452.427,80	589.241
Drainage	32.309,10	35.745,82	41.790,27	59.325,11	59.484,53	61.510,44	61.961,
Urban Area	8.053,95	9.157,83	9.562,19	13.753,30	15.231,25	20.082,34	13.649,
Total	6.142.148,41	6.142.148,41	6.142.148,41	6.142.148,41	6.142.148,41	6.142.148,41	6.142.1

Source: Source: the author (2021).

Based on the table above, it is possible to identify that the three largest classes of use in the Southwest Region of Goiás are agriculture, pastures, native vegetation and an intense growth in sugarcane areas for agro-energy production. Agricultural areas began the analysis period with an occupied area of 1,835,555.15 ha and reached the largest class in the region with 2,090,157.93 ha. Pastureland also had a high regional presence, starting at 1,664,491.28 ha and peaking at 2,260,286.49 ha in 2010. The areas of native vegetation, corresponding to the remnants of the Cerrado, underwent an intense reduction, starting at 2,594,061.05 ha and registering its smallest area of occupation, 1,574,223.31 ha in 2013, which can be seen in figure 4.

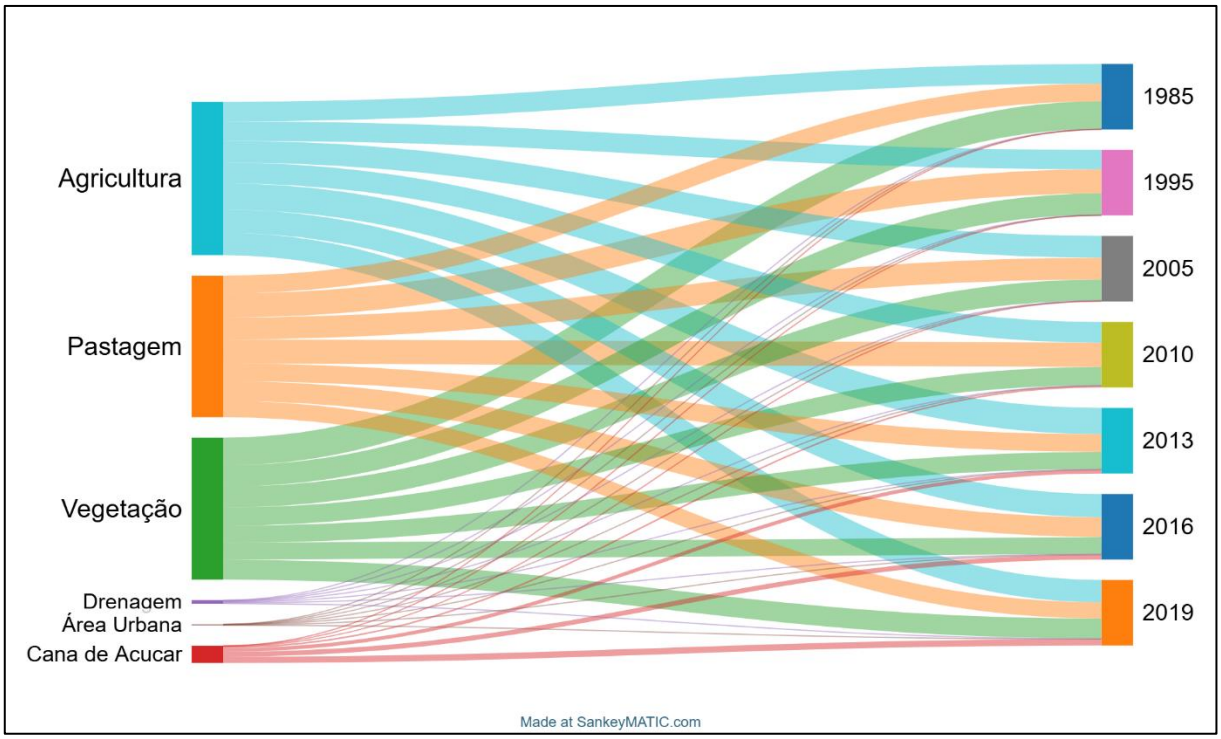

Figure 4- Sankey diagram with land use changes. Source: land use data. Organization: author (2021).

Based on the results of multitemporal land use analyses, the distribution of sugarcane areas in the Center-South region of Brazil, including Goiás, indicates an intense increase related to the period of the new expansion corresponding to the PNA (Rudorff & Sugawara, 2007). This scenario is reproduced in southwest Goiás within this expansion, which intensified between 2005 and 2019, as shown in figure 5.

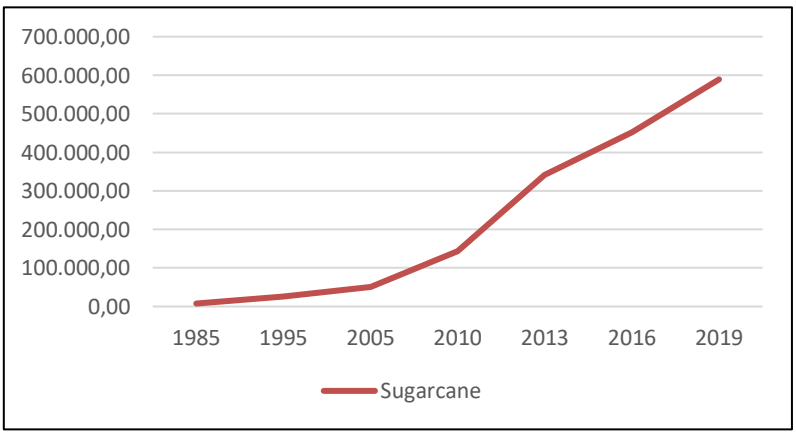

Figure 5 - Expansion of sugarcane in southwest Goiás (Hectares). Source: the author (2021).

The most recent land use results analyzed showed an uninterrupted advance of the sugar-alcohol sector and the recomposition and/or maintenance of native vegetation. This phenomenon can be explained, according to the studies of Abramovay (2019), who describes two realities in the agricultural frontier scenario that presents two processes: the traditional frontier and the technological frontier. The traditional frontier occurs in the face of land use conventions through the direct suppression of land with native vegetation cover converted to agriculture.

The technological frontier is related to the process that employs technological modernization practices, which achieve intense results in productivity, expanding the intense use of areas that have already been deforested. This reduction in vegetation suppression can be associated with the concept of the Borlaug Hypothesis, an expression associated with the relationship between technological intensification of agriculture, which increases productivity and reduces the need to advance into areas of native vegetation, protecting biomes (Borlaug 1983).

A possible reduction in the advance of vegetation suppression in southwest Goiás may be related to this technological development associated with the sugar-energy dynamic, which increases productivity per hectare and does not require new areas, reducing environmental pressure by directly replacing forest resources.

Thus, Abramovay (2019) showed that this technological frontier of Brazilian agriculture, which has been applied in the region, shows that agricultural production is changing its pattern, moving from being land-intensive to technology-intensive, representing an advance also described by Cunha *et al.* (2010), in which the path of technological increase in agriculture presents restrictions on environmental costs, reducing competition for land, water and energy.

From this perspective, the high-performance model adopted by the Brazilian sugar-energy sector may represent signs of a reduction in environmental pressures, mitigating the direct conversion of forests to sugarcane plantations.

Sugarcane in southwestern Goiás has shown itself to be a crop that has grown uninterruptedly since the first policies to encourage the production and sale of ethanol were implemented in the 1980s. Since then, the study region has been consolidated as one of Brazil's main agricultural production areas, especially the meat, grain and biofuel agro-industrial complexes.

Thus, the system related to the advance and competition of these economic practices in Cerrado areas, specifically over native vegetation, is made through the opening up of spaces by pastures that are subsequently filled by economic practices with a higher technological level, being converted by modernized agricultural

practices and the production of biofuels, which compete for areas of higher productivity corresponding to soils with better agricultural aptitude (Trindade 2015).

Agricultural Land Use Suitability and Sugar-Energy Expansion in Southwestern Goiás

Agricultural land use suitability is a model developed to assess the best uses of land, whether for crops, pastures, forestry or conservation. This suitability aims to classify land as good, fair, restricted and/or unsuitable for these uses, taking into account the natural conditions of the soils in relation to their limiting factors, which are fertility deficiency, water deficiency, excess water or oxygen deficiency, susceptibility to erosion and impediments to mechanization. This analysis establishes the best indicated use and its respective level of management based on the greater or lesser involvement of agricultural technologies (Ramalho Filho & Beek 1995).

According to the data collected from the classification of the agricultural suitability of land use, there is a predominance of soils with high and medium suitability for mechanized farming in the southwest of Goiás. The study area recorded 23% of soils suitable for high technology use, 36% for intermediate technology use, 0.06% for low technology use, 33% with use restrictions and 8% for exclusive conservation use (Figure 6). The greater presence of the Latosols class, in areas with low slopes, allows for the development of agriculture with a high level of mechanization, making it attractive for the production of *commodities*, especially in the sugar-energy sector.

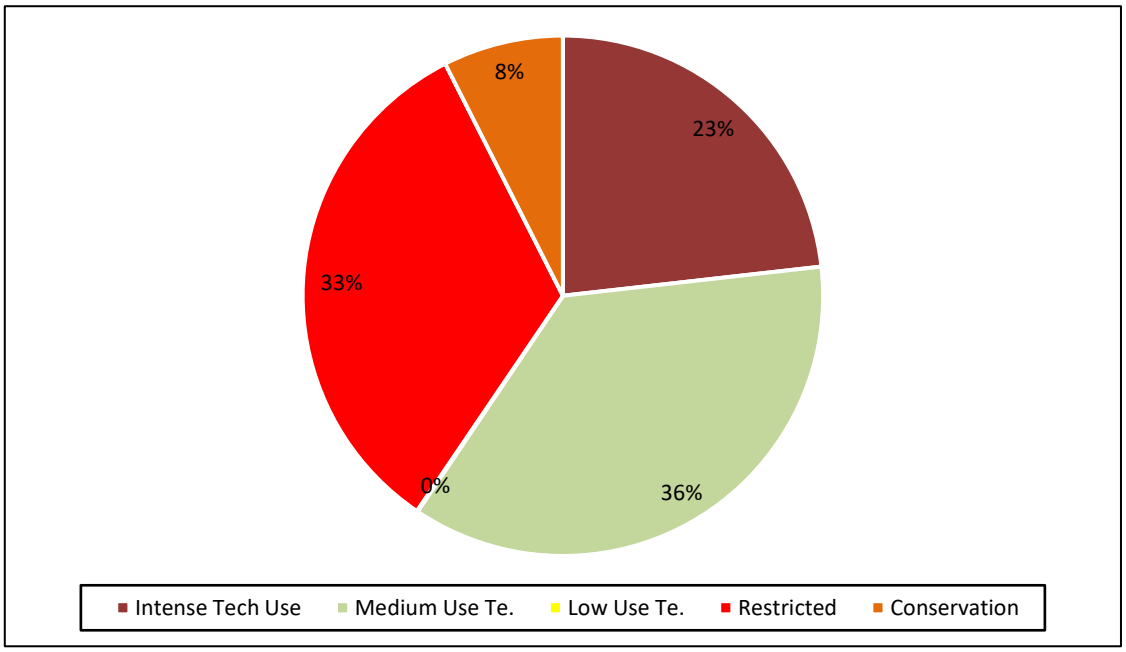

Figure 6 - Agricultural suitability of land use in southwestern Goiás. Source: the author (2021).

The sugarcane production complexes in the southwestern region of Goiás initially developed by taking advantage of the best agricultural aptitude classes, becoming less selective during the last expansion cycle, as can be seen in figure 7.

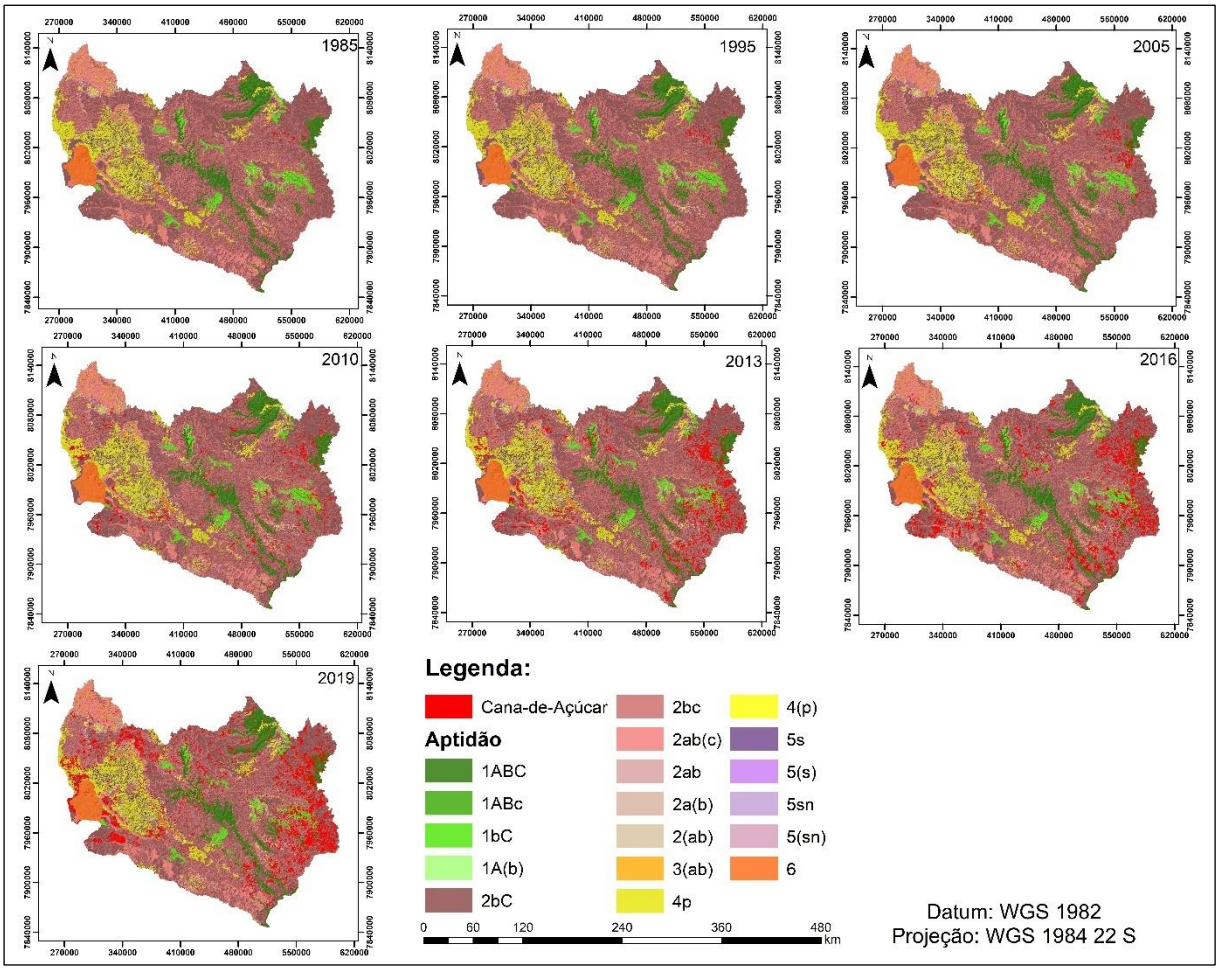

Figure 7 - Agricultural Land Suitability and Sugarcane Production in Southwestern Goiás - 1985 to 2019. Source: the author (2021).

The progression of sugarcane plantations can be better observed in Table 3, which shows the predominance of sugarcane plantations in areas with agricultural suitability in class 1ABC, land with good suitability for crops at management levels A, B and C, in class 1 bC, land that is good for management level C, regular at level B and unsuitable at level A, and in class 2 bc, land that is regular for management levels C and B and unsuitable at level A. Table 3 - The advance of sugarcane in southwestern Goiás in relation to the Agricultural Aptitude of Land Use. Source: The author (2021)

APT class	1985	%	1995	%	2005	%	2010	%	2013	%	2016	%	2019	%
1 ABC	916,7	11,96	3.356,97	13,26	4.299,41	8,46	7.144,97	4,97	20.909,44	6,13	29.510,54	6,531	35.624,15	6,05
1 Abc	0,08	0	48,71	0,19	129,96	0,26	201,59	0,14	955,9	0,28	1.002,06	0,222	1.445,99	0,25
1 bC	2.003,94	26,15	7.439,59	29,39	15.836,75	31,15	40.986,96	28,53	99.657,06	29,24	134.722,81	29,815	168.078,93	28,55
1 A(b)	0	0	0	0	0	0	2,48	0	38,61	0,01	43,52	0,01	75,21	0,01
Total Partial	2920,72	38,11	10.845,27	42,84	20.266,12	39,87	48.336,00	33,64	121.561,01	35,66	165.278,93	36,578	205.224,28	34,86
2 bc	2.003,94	26,15	7.439,59	29,39	15.836,75	31,15	40.986,96	28,53	99.657,06	29,24	134.722,81	29,815	168.078,93	28,55
2 ab(c)	31,3	0,41	388,79	1,54	770,51	1,52	5.541,84	3,86	13.456,23	3,95	16.975,40	3,757	18.518,54	3,15
2 ab	0	0	8,09	0,03	0	0	8,9	0,01	21,69	0,01	11,27	0,002	47,99	0,01
2 a(b)	0	0	84,22	0,33	97,78	0,19	1.022,62	0,71	888,77	0,26	1.157,97	0,256	2.201,31	0,37
2 (ab)	0	0	6,52	0,03	1,67	0	74,7	0,05	33,06	0,01	52,18	0,012	94,98	0,02
Total Partial	2.035,24	26,56	7.927,21	31,32	16.706,71	32,86	47.635,02	33,16	114.056,81	33,47	152.919,63	33,842	188.941,75	32,1
3 (ab)	0	0	16,28	0,06	55,18	0,11	740,37	0,52	1.279,95	0,38	1.423,67	0,315	2.762,24	0,47
Total Partial	0	0	16,28	0,06	55,18	0,11	740,37	0,52	1.279,95	0,38	1.423,67	0,315	2.762,24	0,47
4p	0	0	273,37	1,08	419,76	0,83	8.189,01	5,7	17.501,46	5,13	14.152,05	3,132	31.664,43	5,38
4 (p)	0	0	137,84	0,54	151,3	0,3	1.628,60	1,13	2.627,31	0,77	3.548,83	0,785	6.431,37	1,09
Total Partial	0	0	411,21	1,62	571,06	1,13	9.817,61	6,83	20.128,77	5,9	17.700,88	3,917	38.095,80	6,47
5 s	0	0	123,26	0,49	45,17	0,09	648,83	0,45	2.055,42	0,6	1.511,20	0,334	3.548,05	0,6
5 (s)	0	0	209,4	0,83	122,15	0,24	1.756,87	1,22	2.390,55	0,7	3.738,30	0,827	7.066,17	1,2
5 sn	0	0	0	0	0	0	62,24	0,04	246,9	0,07	164,82	0,036	302,3	0,05
5 (sn)	0	0	0	0	0	0	17,42	0,01	81,59	0,02	162,51	0,036	151,57	0,03
Total Partial	0	0	332,66	1,32	167,32	0,33	2485,36	1,72	4.774,46	1,39	5.576,83	1,233	11.068,09	1,88
6	215,22	2,81	919,57	3,63	1.109,48	2,18	3.117,35	2,17	7.777,96	2,28	8.189,07	1,812	11.713,93	1,99
Total Partial	215,22	2,81	919,57	3,63	1.109,48	2,18	3.117,35	2,17	7.777,96	2,28	8.189,07	1,812	11.713,93	1,99
Total	7.662,98	100	25.316,96	100	50.835,34	100	143.684,65	100	340.880,82	100	451.861,66	100	588.700,69	100

The previous data showed an intense search for the best production areas related to aptitude classes 1 ABC, 1 Abc, 1Bc, 1 A(b), which favor the majority of capital investments in intensive, high-tech production. These results point to a concentration of sugar-energy production with an occupation rate of between 34.86% and 42.84% of the best agricultural land, rising from 2920.72 hectares in 1985 to occupy an area of almost 205,224.28 hectares in 2019, of the soils with the best technological use. Throughout the period analyzed, the advance of sugar-alcohol was also observed on land with aptitude classes 2bc, 2 ab(c), 2 ab, 2 a(b), 2 (ab), which are regular/restricted areas for crops. Occupation of these classes ranged from 26.56% to 33.47%, starting at 2,035.24 hectares in 1985 and reaching 188,941.75 hectares in 2019.

Considering the general groups of agricultural suitability, it can be seen that sugarcane in south-west Goiás has intensified its advance on soils with good suitability and also on regular/restricted areas for agriculture, as well as areas with pasture suitability, especially from 2005 to 2019 with the effects of the National Agroenergy Plan (PNA) (figure 8).

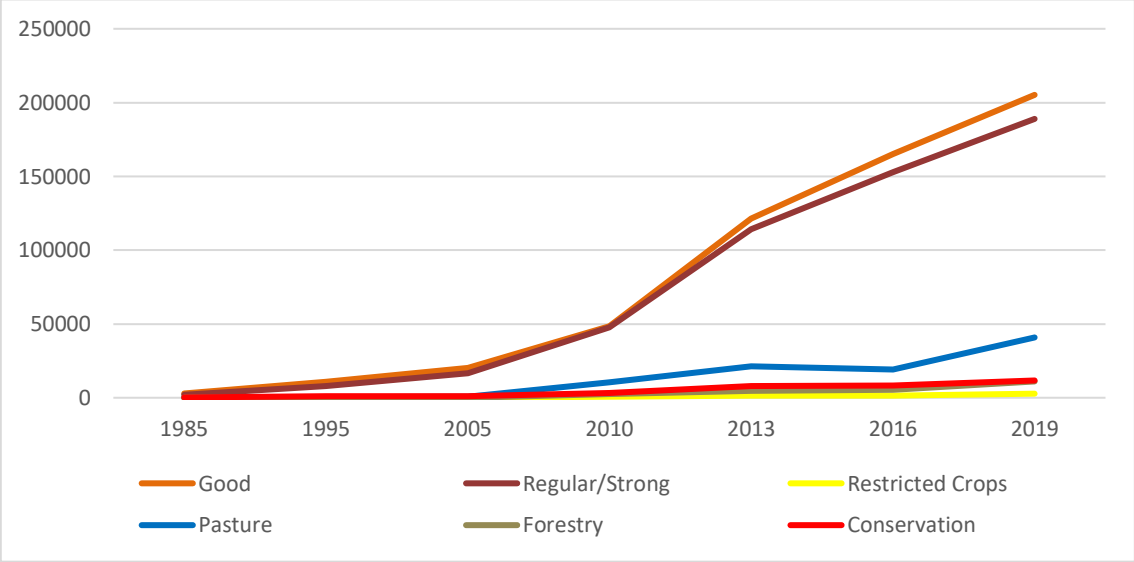

Figure 8 - Advances in aptitude classes. Source: the author (2021).

The advance of the sugar-energy sector onto land with intermediate aptitude for agriculture shows that the ethanol agro-industrial complex, which has always emphasized the most suitable land for the greatest use of capital, has expanded its production areas, creating a scenario for the agricultural frontier in the Cerrado. This process reinforces the basis for planning expansion based on the principles of the Agro-Ecological Zoning of Sugarcane (ZAEcana), which according to Manzatto *et al.* (2009) would take place on land with medium aptitude, especially for degraded pasture areas.

Thus, the dynamics of sugarcane expansion in the southwest of Goiás was based on a productive analysis organized by the quality of the land, and this process suggests that the involvement of the top productive areas

may be associated with what has been described by Chieppe Jr . (2015), who relates this productive profile to the low price of land and high profitability, a scenario that was transformed by the territorial dispute between the other agro-industrial complexes installed in the region during the last agro-energy cycle, forcing them to move into less suitable areas with lower productivity, but with investments in infrastructure as a compensating element.

Logistics Systems and the Expansion of Sugarcane in Southwestern Goiás

The transportation of the sugar-energy sector is one of the major bottlenecks in Brazilian ethanol production and must be analyzed within a national context. The challenge of bringing the production sector closer to consumer markets has created the justification for new logistical investments to serve the ethanol market, as an instrument for regional economic development. The new dynamics of sugar-energy expansion in the southwest of Goiás are influenced by the logistics equipment planned and implemented in the region, creating productive conditions based on the connectivity of the producing regions with the consumer markets of the major national and international centers.

Investments to connect ethanol production areas to distribution and export systems are understood in this study as a new stage of agricultural modernization, based on the Pedological Composition of agriculture, related to the agricultural suitability of the land and logistics. In this concept, the sugar-energy agro-industry is looking for the best physical conditions for the land through the most suitable soils to add to the intense use of agricultural technologies already employed in the sector, augmented by the process of modernizing logistical transport modes. Thus, there is an important relationship between land prices and the dynamics of sugar-energy production, with logistics becoming an instrument to justify the use of land with lower agricultural aptitude.

The southwest of Goiás has been expanding its production by increasing the number of processing plants and, consequently, its planted areas steadily over the last few years. This process has occurred, above all, in the face of government incentives and plans to expand bioenergy production networks in Brazil, through the process of internalizing ethanol production away from the country's major consumer centers. According to Mitsutani (2010), this internalization is due to rising prices and the scarcity of land suitable for planting sugarcane, encouraging the advance of the agricultural frontier to the interior of the country, specifically to the southwest of Goiás.

Ethanol production in this region is advancing thanks to the design of soil factors that guarantee satisfactory productivity in relation to investments, driven by the logistical strengthening promoted by the territorial connection provided by public authorities. Agro-energy production systems benefit from the creation of what Lima (2020) defines as public infrastructure chains created to drive territorial integration in order to advance production towards markets.

The economic moment, in relation to the implementation of the Growth Acceleration Plan (PAC), has contributed to the internalization of sugarcane production, especially in the study area, which has been marked

by new investments in logistical structures to transport ethanol produced in the interior of the country, encouraged by this Plan. From this perspective, the Cerrado areas have benefited from public-private investments in ethanol transportation logistics through the ethanol pipeline project, which is exclusive to the sector, and railways that can serve several different agro-industry complexes located in the region.

The multimodal ethanol logistics system was conceived from the formation of a consortium led by Logum Logística, made up of a consortium of public/private companies. According to the company, it is made up of Copersucar (30%), Raizen (30%), Petrobras (30%) and Uniduto Logística (10%), which has been gradually implementing an exclusive modal system for sugarcane that connects the production regions to the large urban consumer and exporting centers via a system of pipelines and waterways (Figure 9).

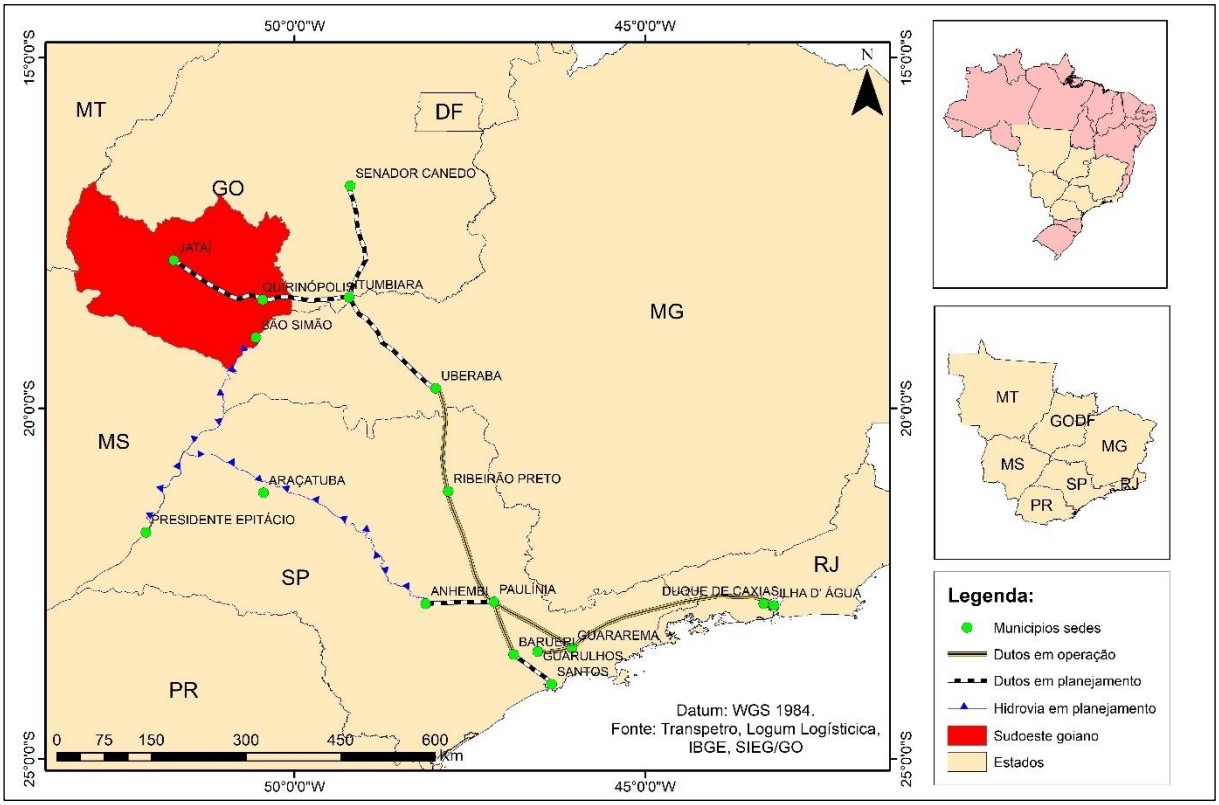

Figure 9 - Logistics systems for the ethanol pipeline and waterways in southwestern Goiás. Source: adapted from Ethanol Logistics System (2020). Org: the author (2021).

This system integrates the country's sugar-energy expansion regions by means of pipelines and waterways that are currently partially operational. The program in its entirety operates a pipeline route linking the Paulínia Refinery (REPLAN), in the city of Paulínia (SP), to the Petrobras terminals located in the cities of Ribeirão Preto (SP) and Uberaba (MG). REPLAN also operates a pipeline system that goes to the Ilhas d'Água refinery, in the city of Duque de Caxias (RJ), passing through the cities of Guararema (SP), Guarulhos (SP) and Barueri (SP) (Logum, 2020).

The pipeline system is being planned for this complex, which will extend a connection to the port of Santos (SP) and, inland, from Uberaba (MG), integrating the system with the state of Goiás, via the cities of Itumbiara

(GO), in the south, Quirinópolis (GO) and Jataí (GO), in the southwest of the state, and the Petrobras distribution terminal in Senador Canedo (GO) in the metropolitan region of Goiânia. In addition to these pipelines, there are plans to make use of the Tietê and Paraná/Paranaíba rivers through a system of waterways. This hydromodal system will be integrated with the REPLAN system, which will pass through Araçatuba (SP), Presidente Epitácio (SP) and São Simão (GO), the latter also in the southwest of Goiás, which will have pipeline and waterway connections (Logum 2014; Barros & Wanke 2012; Mitsutani 2010; Brasil 2008).

Another important logistics system implemented in the southwest of Goiás, through the public policies of the Growth Acceleration Plan (PAC), is the North-South Railway and the North-North Railway, which could influence the flow of sugar-energy by connecting the study area to the production hubs of São Paulo (Figure 10).

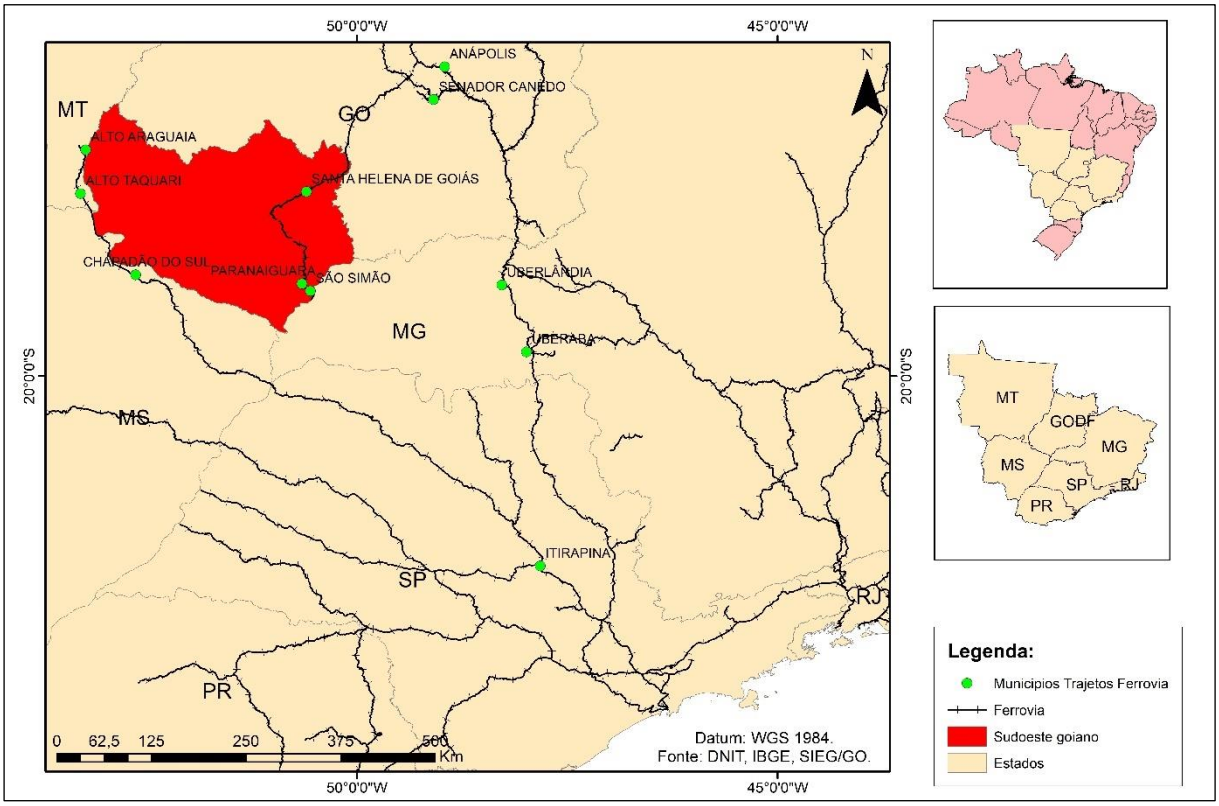

Figure 10 - Logistics systems along the route of the railroads that influence southwestern Goiás. Source: adapted from the Brazilian Institute of Geography and Statistics (2018). Org: the author (2021).

The railroads that make up the distribution system for regional production can be part of ethanol logistics, bringing important benefits related to reducing final product prices and increasing the competitiveness of Brazilian ethanol (Coleti & Oliveira 2019). The structure that constitutes the main production regions of southwestern Goiás through the North-South Railway will include the municipalities of Tuverlândia, Santa Helena de Goiás, Rio Verde, Quirinópolis, Paranaiguara and São Simão during its full operation.

It is interesting to note the logistical integration with the waterway in São Simão (GO), which may stand out among the systems presented. Another extremely important stretch is the Ferro-Norte railroad, which

borders the study area through the state of Mato Grosso, close to the sugarcane production areas located to the west of southwest Goiás, mainly the municipalities of Mineiros, Perolândia, Portelândia and Chapadão do Céu. This stretch of railway connects to the city of Alto Taquari (MT), which is home to important fuel distribution centers through Petrobras, the Alto Taquari Base (BATAQ) and the Raizen Alto Taquari Distribution Terminal, a company resulting from the merger of COSAN and SHELL.

The implementation of logistics modes is progressing as sugar-energy production establishes a high volume per kilometer transported (Mitsutani 2008). The complete operationalization of the publicized systems in southwestern Goiás depends on high productivity, which is temporarily impossible. Therefore, the most mature mode of transport to be used immediately by the sector in Goiás is rail, which represents a more viable system for transporting production on land with lower agricultural potential.

Sugar Production Cells within Pedological Systems

The production of renewable fuels from sugarcane has formed a network of plants in the municipalities of the study area that have been structured based on the relationship between soil and logistics, directly related to the technological factors of production and the natural environment. The locational arrangements of the sugar-energy processing units are defined as the pedological compositions, which take into account the natural conditions and built infrastructure of these municipalities and have an influence on integrated production, with agricultural production technology expanded by transportation modes completing the locational arrangement of agro-energy production (figure 11).

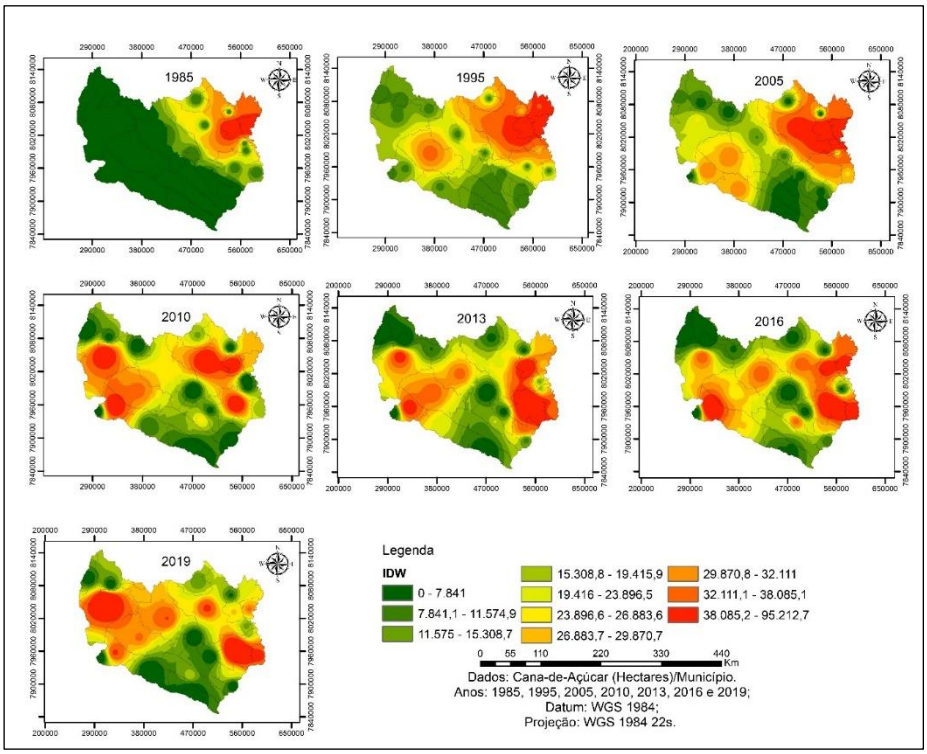

Figure 11 - Formation of the production cells of the sugar processing units in southwest Goiás. Source: the author (2021).

The figure above analyzes the areas of concentration of sugarcane mills by municipality in the southwest of Goiás from 1985 to 2019, based on the Interpolation of Points by Weighting the Inverse of Distance (IDW), which are distributed based on the locational factor established by the criteria of agricultural suitability and logistical flow, consolidating the temporal relationship distributed based on these two factors. In this way, it was possible to observe the progression from two *core* areas, defined here as ethanol production cells - East and West - which were influenced by the quality of the agricultural use of the land and the logistics provided.

It can be seen that the *core* sugarcane area in the region in 1985 was the municipality of Santa Helena de Goiás and Tuverlândia and its surroundings. In the period analyzed below, it was observed that in 1995 this concentration still remained in this region, branching out to Rio Verde and Acreúna. There was a slight emergence of a production cell in Serranópolis in the westernmost part of the region. This data shows that the initial concentration of mills in the region was based on factors related to agricultural suitability, with the easternmost part having the best soils for growing sugarcane.

From 2005 onwards, a period related to the latest sugarcane expansion under the National Agroenergy Plan (PNA), it was possible to observe the expansion of the East Cell, which occurred as a result of increased production in the *core* area. In the same period, it was possible to observe the beginning of the division of the West Cell with its respective strengthening, reaching Serranópolis, Chapadão do Céu and Aporé. Also in this period, there was a predominance of production involved with the suitability of the land, in which the sugarcane sector possibly established itself on the areas with the best levels of management, but with the start of regional logistical influence, a process influenced by the announcement of the ethanol pipeline and also by the North/South railroad.

In 2010, the East Cell was expanded to include the region of Quirinópolis. Along with this new dynamic, the West Cell was consolidated through increased production in the municipalities of Chapadão do Céu, Mineiros and Serranópolis. In this period, the consolidation of two nuclear production axes from the East and West Cells was evident, and this consolidation was possibly due to the influence of soil factors added by the implementation of the railroad route, making up the logistical influence on this new sugarcane spatial dynamic.

In 2013, the spatialization of sugarcane cultivation saw changes in the production nuclei in which the East Cell established a new *core* area represented by Quirinópolis, while the concentration in Santa Helena de Goiás decreased. On the other hand, the West Cell has seen an intense increase in its influence, including the municipality of Jataí. These changes can be interpreted in light of the important rail routes and the pipeline connection with its planned route in the municipality of Jataí to Senador Canedo, as well as the waterway from São Simão, both of which are being planned.

In 2016, the East Cell remained between the municipalities of Santa Helena de Goiás, Turvelândia, Rio Verde, Quirinópolis, expanding production to Gouvelândia and Acreúna. In the west, Chapadão do Céu, Mineiros, Serranópolis and Jataí remained, with the start of a third production cell located in the south of the region, specifically in the municipality of Caçú. This distribution can be explained by the completion of the

North-South Railway in Goiás and the connection of Ferro-Norte, which integrates São Paulo with Mato Grosso, via the Alto Taquari (MT) distribution center, which borders the West Cell of ethanol production, under the influence of the Logum System, since the pipelines and waterway did not advance beyond the municipality of Uberaba (MG). In addition to the importance of railroads in influencing the distribution of sugar-alcohol production, it can be seen that sugarcane in the West Cell is expanding into areas with better agricultural aptitude in Portelândia and Perolândia.

Finally, in 2019, the East Cell now has its core area in Quirinópolis and Gouvelândia, reducing the productive importance of the other areas, except for Rio Verde. This production redesign can be explained by the succession of economic impacts that permeated a crisis scenario in the municipality of Santa Helena de Goiás and the surrounding area. The West Cell was expanded and consolidated, forming a production corridor between Chapadão do Céu, Serranópolis and Jataí, with the emergence of a corridor integrating the East and West Cells, interconnected by the municipalities of Jataí and Rio Verde. The influence of these areas, from a logistical and edaphic point of view, which aggregates pedological variables, with the best soils, the regions served by the railroads and the route of the future alcohol pipeline from the perspective of its connection with the southwest of Goiás.

Conclusions

The advance of the ethanol agro-industrial complex in the southwest of Goiás showed intense growth in its last phase of expansion, influenced firstly by the agricultural suitability of land use and later by the conditions for the creation of logistical instruments. This progress occurred through an increase in the number of ethanol production plants, reaching 16 (sixteen) plants in operation, and ~590,000.00 hectares planted in the last period analyzed, distributed over 26 (twenty-six) municipalities during the period studied.

The pedological composition of sugarcane is a new stage in the modernization of regional agriculture. This initially uses natural soil conditions as the main production factor, followed by the use of technological equipment to transport production at low cost. The soils with high agricultural aptitude offer the necessary attractiveness for the installation of sugar-alcohol projects, complemented by the logistical infrastructure, which establishes the viability of large agro-industrial investments in soils with lower aptitude.

The suitability of land use in southwestern Goiás showed that sugarcane production first advanced onto land with greater suitability for mechanized crops located in the east of the region, moving on to areas of less suitable land, with restrictions on mechanization and suitable for pasture, forestry and even preservation. This shows that sugarcane production has sought out the areas with the greatest production potential and agriculture already consolidated by other agro-industrial complexes, which are more highly valued regions, moving on to areas with cheaper land.

The logistics complex structured for ethanol transportation in southwest Goiás is officially made up of the ethanol logistics system plan, which connects the region to consumer and export markets via pipelines and waterways. However, regionally, the railroads have gained greater prominence over the ethanol-only modal

system due to their completion and ability to serve the other agro-industrial complexes in the Midwest of Brazil. Thus, railroads complement the technological package of regional agriculture, including sugarcane, and are a regional diffusion mechanism for this sugarcane expansion, making it possible to produce renewable fuels in areas with comparative lower land prices.

The advancement of the sugar-energy sector in southwestern Goiás has established a process that differs from the use of agronomic applications linked to the expansion of production. The advance in the implementation of logistics modes occurred to the extent that sugar-energy production established a greater volume per kilometer transported, which led to changes in production areas with new axes of sugarcane expansion, in which production concentrations remained in areas with the best soil resources and made it possible to invest in land with lower agricultural aptitudes for mechanization through the opening of new biofuel production cells in the Cerrado.

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