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# Sustainability dynamics of the Brazilian MATOPIBA region between 1990-2018: Impacts of agribusiness expansion

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ABSTRACT

MATOPIBA is a Brazilian region with 73.2 million ha that has been facing a change in its land use due to agribusiness expansion over the last thirty years. The sustainability-related issues of this land use change raise doubts since it may result in advantages and/or disadvantages for social, economic and environmental aspects. This work assess the sustainability of MATOPIBA by means of a sustainability assessment procedure for operations and production processes (SUAPRO), covering the period 1990–2018 by including both the phases before and after agribusiness expansion. Expressed by the sector sustainability indicator (SSI) from SUAPRO, results show that MATOPIBA's sustainability macroeconomic and social (as the provider function) sectors are increasing along years, while environmental and social (as the receiver function) sectors are worsening. Focusing on MATOPIBA's overall sustainability, the sustainability synthetic indicator of system (SSIS) showed the worst performance for 2000 (4.71) and the best one for 2010 (3.63), while 1990 and 2018 obtained intermediary SSIS values of 4.17 and 4.51. The obtained pulsing behavior for SSIS does not support a conclusion about whether MATOPIBA's overall sustainability is increasing or even decreasing over time, claiming for future efforts to include additional data after 2018 year. Notwithstanding, there is a potential to achieve the maximized SSIS of 1.65 whether the identified actions for improvement were implemented. Besides providing subsidies for decision makers towards a more sustainable MATOPIBA, this work innovates by using nightlights satellite images as a proxy in obtaining data for modelling the SUAPRO.

## 1. Introduction

A sustainable world that is truly comprehensive should incorporate social equity, the elimination of poverty and hunger, safeguarding of human rights, gender equality, resilience to climate change, sustainable consumption and production, peace, governance, and partnerships. Equally significant is the need to translate this expanded vision of a more sustainable world into quantifiable objectives and metrics (Bettelli, 2021), such as the UN (2020) proposal for goals to achieve sustainable development, helping strategic planning and its execution. Among several other productive sectors, the agribusiness sector deserves attention due to its close relationship with different UN sustainable development goals (SDGs), including food production (SDG#2, zero hunger) through economic activities and jobs generation (SDG#8, decent work and economic growth), but at the same time it may have influence on social aspects related to urbanization increase (SDG#1, poverty; SDG#11, sustainable cities & communities) and on the natural environment related to themes such as biodiversity, changes in soil characteristics, and greenhouse gas emissions (SDGs#13 and #15, climate action and life on land). Brazil was ranked as the 1st largest net exporting country of food (excluding fish) in 2020, achieving 64 USD billion (FAO, 2023a). According to FAO (2023b), Brazil was in 2021 the 1st world exporter of soybean (53%), chicken meat (27%) and cattle meat (20%), the 2nd exporter of cotton (21%), and the 4th for maize. As one of the world's leading countries in the agribusiness sector, Brazil is under international pressure to reduce deforestation and greenhouse gas emissions (Silva Junior et al., 2021; Lapola et al., 2014; Rajão et al., 2022 – opposing to fake scientific controversies), while meeting the

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growing demand for food production. One of the main challenges for Brazilian development is to maintain the growth of its agricultural production while reducing the impacts on its natural resources. According to Kruid et al. (2021), the reduction of $CO_2$ emissions mainly in landing grabbing (including the indirect ones as highlighted by Coscieme et al., 2016) and illegal deforestation areas should receive special attention.

The Brazilian government has reduced its direct involvement in national agricultural production since the early 90's, allowing the private sector to increase its power from a more liberal economic approach, including the creation of new agricultural frontiers in the natural savanna biome (Alston et al., 2016) that occupies 25% of the national territory in the Midwest and Northeast regions. A region that was previously almost entirely occupied by natural vegetation has been replaced by agriculture. The most recent agricultural frontier of the Brazilian savanna is located in the northeast region and is called 'MATOPIBA' (which includes the states of Maranhão, Tocantins, Piauí and Bahia). With 73 million ha and 6 million inhabitants, it is a region characterized by poor infrastructure but with land prices well below the market compared to other Brazilian regions, in addition to having a favorable weather and land-slope for agribusiness activities (Favareto, 2019). Even though it began in the early 1990s and its intensification occurred in the 2000s, it was only after three decades of advancement in agribusiness in MATOPIBA that the Brazilian government sought to regulate this agricultural area in the form of the Federal Decree no. 8447 of 6th May 2015, establishing the Agricultural Development Plan for MATOPIBA (ADP-MATOPIBA). The objective is to promote and coordinate public policies for the economic and sustainable development of agricultural activities in the region, proposing guidelines for programs, projects and federal actions towards better quality of life for the local population and national economic growth (Araújo et al., 2019; BRASIL, 2015).

Several studies from different disciplines and purposes are being carried out in the MATOPIBA region, discussing advantages and disadvantages of agribusiness expansion in that region. Positive criticisms of ADP-MATOPIBA are mostly related to implementation of agro-industries that can increase production efficiency according to regional realities, by considering its potential for regional socioeconomic improvements. For example, Buainain et al. (2018) understand that people from other regions will bring and disseminate accumulated knowledge and experience for regional development, a productive change through cultural transformation; Bragança (2018) argues that agribusiness expansion leads to gross domestic product (GDP) per inhabitant increase and access to durable goods and basic infrastructure by population; and from an environmental perspective, Locatelli et al. (2022) have found that replacing natural vegetation (savanna) by non-tillage crops does not alter carbon and nitrogen stocks in the soil. Although recognizing the existence of benefits from agribusiness expansion, Medina and Santos (2017) emphasize the need for more realistic assessments of land use changes led by different stakeholders and considering different scales for evaluations.

Negative criticisms are mostly related to the extinction of natural capital and its derivate environmental services, money concentration, increase of poverty, and extinction of small and traditional agricultural producers. For example, Polizel et al. (2021) emphasizes that about 8.4 Mha of native vegetation areas were mostly converted into agricultural lands, and that 57% of the identified issues regarding the Brazilian Forest Code occurred in large properties, which is much lower in absolute numbers than small rural properties. Santos et al. (2019) claim for changes in the Brazilian legislation for biodiversity protection, in which the connectivity among natural protected areas must consider its connectivity to avoid fragmentations and consequent biodiversity losses. Xavier (2019) calls attention to the fact that agribusiness expansion is based on the business-as-usual pattern of money accumulation and production of primary goods for exportation, instead of regional development. Rasmussen and Lund (2018) understand this kind of territorialization as dissolving existing social orders, patterns of social control, authority, and institutional orders. Russo Lopes et al. (2021) identified the existence of a process of environmental degradation and resource dispossession, claiming that the vague discourse that agribusiness expansion brings development for all must be rethought to avoid unbalances. Santos et al. (2021) have found that converting natural vegetation into agribusiness crops through non-tillage techniques increases soil compaction by reducing soil porosity, and the proportion between water and air in the soil reaches critical levels for agricultural purposes. De Oliveira Santana and Simon (2022) argue that MATOPIBA's flora is rich with about 54 endemic and 38 threatened species, and those remaining are still under pressure due to agribusiness expansion, which Schneider et al. (2021) have named as "Brazil's next deforestation frontiers". Pompeu (2022) suggests that MATOPIBA areas containing endemic and threatened populations should remain untouched to avoid the loss of rare species.

Even recognizing some benefits resulting from the advance of agribusiness in MATOPIBA, some authors call attention to the importance of using a holistic approach when discussing the advantages and disadvantages of this new agricultural frontier. For example, Buainain et al. (2018) argue that despite the economic importance of agriculture in MATOPIBA, questions still arise about the extent to which the mobilized investments will truly result in more sustainable activities, and to what extent agribusiness will have the strength to lead development – to its full definition – in states that are traditionally poor and with a high population density in rural areas. According to IPEA (2019), one can observe the improvement of MATOPIBA's macroeconomic performance indicators in recent decades, but at the same time there are social indicators with very low performance. The region faces serious social problems such as misery and chronic poverty of the local population, a result of the high concentration of income that is often masked by macroeconomic indicators (Favareto, 2019). Regarding environmental aspects, BRASIL (2016) reported that MATOPIBA's agricultural potential can be negatively affected by a high degradation degree and soil desertification, a result of traditional and non-ecological practices of agricultural management adopted in the region. This raises doubts about whether the identified economic growth also leads to an improvement in the regional sustainability – including its population –, emphasizing the importance of better understanding the drivers and relationships resulting from the occupation dynamics in this region. Precisely, it is necessary to better understand how the advancement of agribusiness contributes to sustainability (including economic, social and environmental aspects) at different scales and existing sectors in MATOPIBA.

All these scientific findings reflect the existing complexity when dealing with sustainability studies of agribusiness expansion in the MATOPIBA region, as also happened in other parts of the world including the northeast China in the 20th century, and more recently in Mozambique, Africa, with the ProSAVANA program. MATOPIBA becomes an important case study to allow discussions about the economic and socio-environmental development binomial in regions. The research question that supports the development of this work is: Does the advancement of agribusiness in the MATOPIBA region result in higher regional sustainability?

Sustainability assessments are mandatory to supporting policies, strategies, and action plans towards a more sustainable future. According to Giannetti et al. (2019), sustainability assessments should be based on scientific bases, initially establishing definitions and concepts, and then proposing epistemologically representative conceptual models supporting indicator choice. Even though there is a profound debate in the scientific community on how to quantitatively assess the sustainability of regions (among others, Cracolici et al., 2018; Pulselli et al., 2006; Salvati & Carlucci, 2014), the recent proposal of Sustainability Assessment Procedure for Operations and Production Processes (SUAPRO; Agostinho et al., 2019) appears as an alternative approach. SUAPRO is based on the 'PDCA' management tool (plan, do, check, act), on the ISO 14,000 series standards related to life cycle analysis (ISO, 2006), and on the Five Sectors Sustainability Model (Giannetti et al., 2019). Besides using SUAPRO, this work proposes its synergistic use with geographical information systems (GIS) as an alternative to obtain raw data on a regional scale (Agostinho et al., 2021). This approach is applied to overcome the lack of available and reliable databases for large regional scales.

This work aims to use GIS-based SUAPRO to quantify the sustainability of the MATOPIBA region between 1990 and 2018 to allow discussions on the regional sustainability dynamics due to agribusiness expansion in both periods, before and after its intensification. From a practical perspective, this study provides scientific-based information to support public policies towards a more sustainable MATOPIBA, but that can easily replicated in any other similar region of the world. From a theoretical perspective, this work contributes to the advancement of science in the topic of sustainability of regions, as it proposes the simultaneous use of GIS with nightlight satellite images to feed SUAPRO with data.

## 2. Methods

### 2.1. Study area description

In the mid-1980's in Brazil, a new agricultural frontier known as MATOPIBA (Fig. 1) began, a region that underwent intense social and environmental transformations with large agricultural projects popping up (Embrapa, 2018). MATOPIBA is composed of 31 administrative micro-regions, formed by 337 municipalities of four federative states (Maranhão, Tocantins, Piauí and Bahia, whose initials form the word MATOPIBA), with 73.2 million ha and 6.3 million inhabitants. The changing landscape was accelerated in the early 1990s by farmers that migrated from the Brazilian southern region, attracted by the cheap land prices and favorable weather conditions for crop production in large areas dedicated to exportation (Aguiar & Monteiro, 2005). Due to the crop production, mainly soybean, the MATOPIBA region has converted its traditional agriculture of small areas based on subsistence structures into large areas with high-tech agriculture, facilitated by government funding on road and rail infrastructure. MATOPIBA's GDP achieved 53 R$ billion during 2010's (Favareto, 2019), emphasizing its macroeconomic importance.

According to the OECD/FAO (2015) report, the agribusiness expansion in the Brazilian North and Northeast regions started in the 1990's supported by national neoliberal policies. The open market allowed strong investments from private capital, controlling the upstream agricultural production by providing credit and goods, and the downstream side by processing, transporting, and selling the produced crops. Table 1 presents the land use dynamics in MATOPIBA between 1985 and 2018 that shows the conversion of areas with natural vegetation (forest and non-forest) into agricultural areas, which tripled during the period. From the 2000's, the agribusiness expansion intensified by using high-tech equipment and machinery, and application of fertilizers and soil amendments that has changed the regional economy and reached a significant share of national agricultural production (Embrapa, 2018). MATOPIBA presents many specificities due to its immense territory, including enormous social, economic, and productive disparities (Favareto, 2019), at the same time, MATOPIBA has biophysical characteristics favorable to agribusiness such as

**Table 1**
Land use dynamics of the Brazilian MATOPIBA region. Values in 1000 ha. Source: MAPBIOMAS (2019).

| Land use | 1985 | 1990 | 2000 | 2010 | 2018 |
|---|---|---|---|---|---|
| Natural forest | 53,600 | 52,700 | 49,600 | 46,300 | 42,700 |
| Non-forest natural formation | 11,300 | 11,400 | 11,200 | 10,400 | 9300 |
| Agriculture and livestock | 7150 | 8160 | 11,600 | 15,500 | 20,000 |
| Unvegetated area | 523 | 391 | 404 | 403 | 596 |
| Water bodies | 555 | 463 | 422 | 507 | 566 |
| Non-observed | 29 | 29 | 29 | 29 | 29 |
| Total | 73,200 | 73,200 | 73,200 | 73,200 | 73,200 |

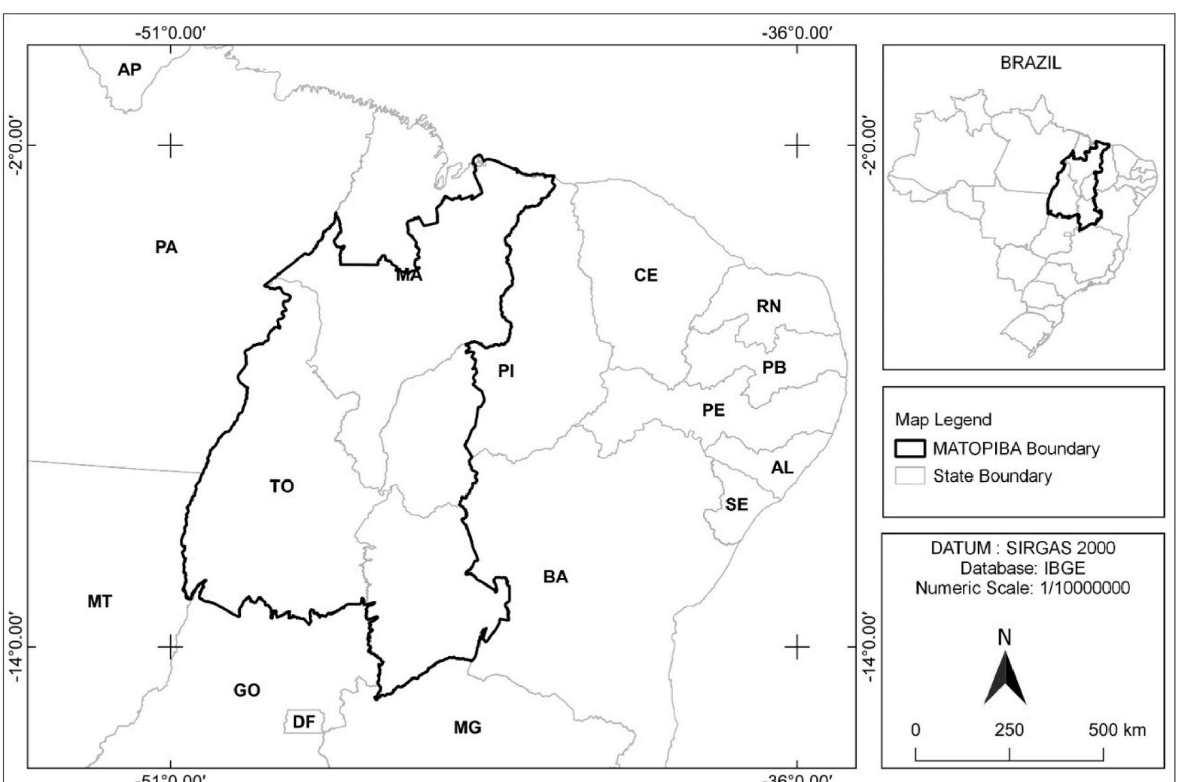


**Fig. 1.** Spatial boundaries of the Brazilian MATOPIBA region. Map based on Embrapa (2018).

appropriated land slope for mechanization, soil types, and annual rainfall frequency that supports the usage of modern productivity techniques (Lima et al., 2019). According to Embrapa (2018), the agribusiness expansion in MATOPIBA is favored by access to technologies currently used in agriculture, such as the use of hybrids and cultivars adapted to regional edaphoclimatic characteristics, good practices for efficient fertilizers use, available pesticides, and conservation management systems as the no-tillage and crop-livestock-forest integration. For Lima et al. (2019), Souza et al. (2020) and Magalhães et al. (2020), the agricultural expansion over natural savanna areas was boosted up after the signature of the Amazon Soy Moratorium in 2006, which prevented the opening of new agricultural areas over areas of tropical forests in Brazil.

According to Xavier (2019), agricultural production in MATOPIBA has been mostly destined for international markets, repeating a pattern of production and accumulation based on the exportation of primary goods, the so-called export pattern of specialization and productivity. In the literature review developed by Rasmussen and Lund (2018), authors have found this production pattern dissolves the traditionally existing social orders such as property systems, human rights, and social contracts, opening space for new forms of social control. In MATOPIBA, the main economic funding supporting agriculture is foreign capital, especially investment funds that speculate with agricultural land and transform it into financial assets. Thus, the importance of the Brazilian government in regulating and controlling the territory becomes evident, acting as an inspection agent and as a promoter of public policies and legislation (Pitta et al., 2017). This characteristic reinforces the hypothesis that land speculation is the ultimate goal of agribusiness expansion rather than agricultural production, as there are no public policy discussions beyond the agricultural exporter focus (Pereira, 2019). Even with all these negative aspects, Buainain et al. (2018) argue that economic dynamics in MATOPIBA due to agribusiness is a decisive driver in decisions by private agents, which could be better used to promote regional development and public policies formulation that would be more appropriate to the local reality, justifying agribusiness in the region.

Agribusiness is not the unique production system existing within MATOPIBA region, since there are industries and services sectors operating as well, however agriculture is the main regional economic driver. For example, Pereira et al. (2018) argues that from the total GDP generated by MATOPIBA in 2013, the agribusiness was responsible for 19%, while industries 16% and services 65%, however, these authors and Bragança (2018) emphasize that services sector is strongly related to agriculture (transport, harvested-crops storage, agricultural equipment storage, infra-structure for logistics, technical assistance, etc.). Notwithstanding, Table 1 shows agribusiness occupying an area about 13, 21, 28 and 33 times larger than the area occupied by urbanized systems (unvegetated area) for the same years, indicating its spatial representativeness. Saying that, and allied with studies of Sá et al. (2015), Bragança (2018), Pereira et al. (2018), Araújo et al. (2019), among others, the main driver for MATOPIBA dynamics on economic, social and environmental issues can be considered as almost exclusive a result of the agribusiness activity.

Given its economic, social, and environmental importance, the MATOPIBA region becomes a relevant case study to support discussions on public policies for a more sustainable agribusiness expansion in large areas traditionally occupied with natural vegetation, such as the agricultural development plan (ADP) for MATOPIBA. Nevertheless, it is important to highlight that method and discussions applied in this study can be easily replicated in any other region of the world.

### 2.2. Sustainability assessment procedure for operations and production processes (SUAPRO)

According to Agostinho et al. (2019), SUAPRO is a framework epistemologically rooted in scientific concepts and definitions regarding sustainability and management issues, to allow the efficacy of studies about the sustainability of production systems. It overcomes the lack of structured scientific procedures by providing systematic activities to be developed with the ultimate goal of making diagnoses and proposing actions towards sustainability. Due to its advantages, when compared to other existing procedures available, the SUAPRO framework is used in this work as a tool to better understand, and quantitatively evaluate the sustainability of the MATOPIBA region. Fig. 2 shows how SUAPRO is organized in different stages and activities. Stage 1 covers the initial aspects such as defining the objectives of the study, scope, functional unit, and it suggests elaborating an energy diagram as a conceptual model representing the studied system. Stage 2 focuses on chosen and obtaining indicators that will feed the 5SEnSU sustainability model. Stage 3 quantifies the sustainability of the studied systems by normalizing, establishing weights and goals before applying the goal programming philosophy based on the 5SEnSU model. Finally, Stage 4 focuses on proposing improvements for the studied system, including a sensitivity analysis. These four stages cover the four existing macro-stages of the ‘plan, do, check, act’ management concept, allowing the continuous application of SUAPRO to improve the sustainability performance of the studied system. All these stages are individually and detailed presented in the next sections.

#### 2.2.1. Stage #1 – Contextualizing the assessment

The SUAPRO framework is applied to better understand MATOPIBA’s sustainability dynamics and allow discussions about whether and how the agribusiness expansion is affecting regional sustainability. Based on the 5SEnSU model, is possible to disaggregate the analysis from macro to micro levels and identify strengths and weaknesses according to the five sectors that includes the natural environment (as provider and receiver), economic, and social (as provider and receiver). To achieve this main objective, the spatial scale (system boundaries) adopted in this study is the physical limits of the MATOPIBA region, as previously presented in Fig. 1.

Regarding the temporal scale for analysis, it includes the years 1990, 2000, 2010 and 2018. These years were chosen based on two criteria: (i) they encompass the temporal changes in MATOPIBA due to agribusiness expansion, including the periods before and after agricultural intensification; (ii) availability of raw data according to the agricultural census of the Brazilian Institute of Geography and Statistics, which usually takes place every ten years. Although the process of occupation in MATOPIBA started between the 1970’s and 1980’s, it was only from 1990’s onwards that agricultural production was intensified to produce crops on a large scale, but still in an incipient way. Between 2000 and 2010, the region become an agricultural frontier, with emphasis on large-scale agribusiness production for exportation. The year 2018 was chosen to represent MATOPIBA after the national agricultural development plan had been implemented in the region.

In addition to its academic-scientific contribution, this study can support the establishment of public policies related to agribusiness advancement in MATOPIBA, including government agencies (Federal, State and Municipal scales), in addition to being useful to private regional companies that operate directly in agribusiness, allowing them to better understand their impact on regional sustainability and seek actions for improvements. Teaching and research institutions, and civil society organized through NGOs can also benefit from the results of this study.

Primary data feeding the modelling is obtained from many different sources, including governmental reports, databases, scientific articles, and shapefiles used in the elaboration of thematic maps through GIS; all data sources are presented in Appendix A. Due to MATOPIBA’s complexity, including its different by-products and large scale representativeness, the choice of functional unit was based on the importance of considering all data relative to the area (in hectares) as a way to ensure that each hectare would have the same average characteristics distributed throughout MATOPIBA. Thus, there is not a defined

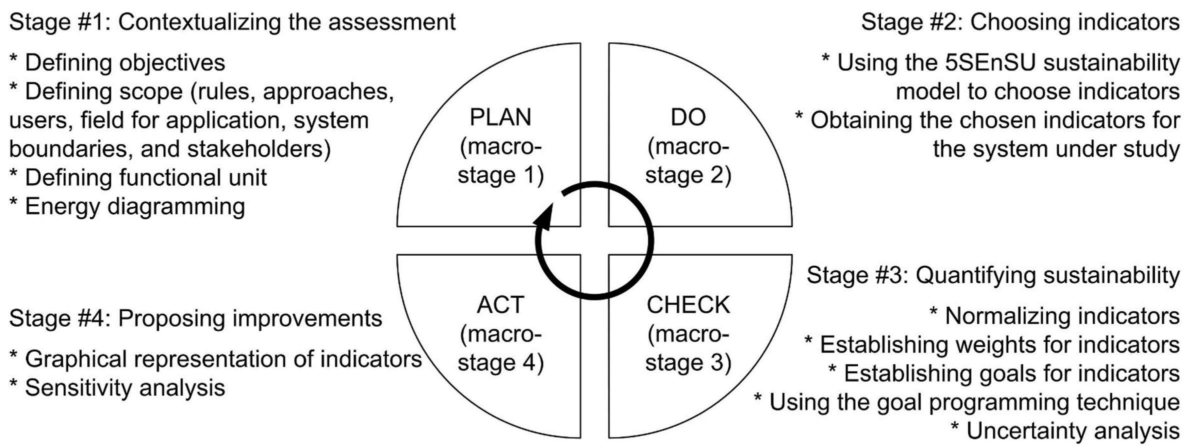


**Fig. 2.** The 'plan, do, check, act' (PDCA) concept supporting the stages within SUAPRO. Source: Agostinho et al. (2019).

functional unit in this work – in its classic definition by ISO 14,000 series –, instead, data and indicators were converted to reflect the spatial performance per hectare of land in the region. This approach is usually found in scientific literature that deals with studies of regions, including life cycle assessments, emergy synthesis, among others.

*2.2.2. Stage #2 – Choosing indicators*

The Five Sectors Sustainability Model (5SEnSU) is used to support quantitative sustainability evaluation by SUAPRO. Among others available conceptual models, 5SEnSU was chosen because it is an holistic model that comprises multi-characteristics, including multi-dimension (social, environmental and economic dimensions), multi-view model that takes a stand from the natural environment, from the society and from the production unit, multi-metric characteristic through the inclusion of indicators from different methods, and finally a multi-criteria approach since it considers a combination of indicators with different weights and goals. Understanding that human-driven systems are open systems with energy and matter flowing and generating products and concentrated by-products, Pulselli et al. (2015) proposed the input-state-output (environment–society–economy) sustainability model as a way to bring epistemological basis for sustainability discussions. As a modelling advance, the 5SEnSU was proposed by Giannetti et al. (2019) recognizing that inputs and outputs have two different perspectives: donor and receiver sides (Fig. 3). Besides considering the two axioms proposed by Daly (1990) when dealing with sustainability issues (i.e. nature providing resources and diluting by-products), the 5SEnSU also considers the importance in existing a balance in nature as providing resources and diluting by-products, it recognize that production of goods must respect the biophysical restrictions of nature and that society must have a responsible consumption, and finally it understands that man acts as labor provider and receiver of goods from the economy. It is not the intention to exhaust the subject in this paper, so the works of Giannetti et al. (2019) and Agostinho et al. (2019) should be considered as references for more details about mathematical approach behind the model, as applied in the Supplementary Material A. The 5SEnSU model has been used in other studies, including sustainability assessment of rice production (Moreno Garcia et al., 2021), the relationship between circular economy and sustainability (Terra dos Santos et al., 2022, 2023), water and wastewater treatment plants (Giannetti et al., 2022), and to discuss about poverty traps existing in underdeveloped countries (Giannetti et al., 2023).

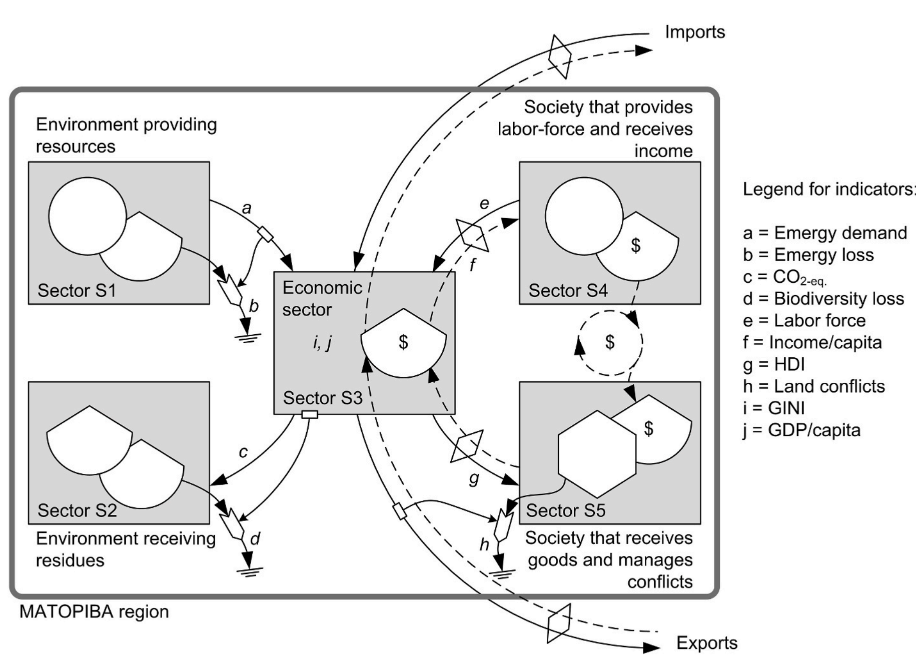


**Fig. 3.** Modelling MATOPIBA's sustainability based on the 5SEnSU.

The task of choosing indicators must respect the restrictions imposed by the 5SEnSU model according to the sectors involved (environmental, economic, or social) and its roles as donor or receiver. According to Agostinho et al. (2019), the indicators that feed the 5SEnSU can be based on the individual analyst's expertise or be based on participatory techniques considering the opinion of several experts, but always considering the following quality parameters as suggested by Bonisoli et al. (2018): data availability, relevance, analytical validity, flexibility to change, measurability, relevance to public policies, ease of implementation, and ease of understanding. Fig. 3 presents the 5SEnSU model representative of the MATOPIBA region with the chosen indicators for analysis. The choice was initially based on the expertise of the authors of this work, and then validated by the research group on Cleaner Production in which authors collaborate.

Two indicators are considered to represent each sector of the 5SEnSU model, as described in Fig. 3 and Table 2. Sector S1 includes the emergy demand (with 'm'; Odum, 1996) by MATOPIBA and the emergy loss in terms of soil erosion and natural vegetation area reduction, both in sej/ha yr (sej means solar emjoules, the unit measure for emergy). Emergy indicators are appropriate to represent sector S1 because emergy refers to the effort done by the natural environment in providing resources for human processes, recognized as a donor side perspective in understanding value. An original contribution of this study is related to the 'emergy calculation for urban areas', an input flow within the emergy accounting table of MATOPIBA. Since obtaining data for municipal and or regional scales to apply emergy synthesis is a hard task when accurate and updated databases are unavailable, this work applies the synergic use of GIS with nightlights satellite images as a proxy in estimating the emergy for urban areas. Agostinho et al. (2021) proposed this approach and they provided a model to estimate emergy from the sum of lights, which was slightly adapted and applied in this present study. Appendix A and Supplementary Material B provide detailed calculation procedures.

For sector S2, environmental burden indicators are used to represent the natural environment as a receiver role, including greenhouse gas emissions (ton$CO_{2\text{-eq.}}$/inhabitant yr) and biodiversity loss (species/yr) that act as MATOPIBA's energy drains and jeopardize its full operation. S3 represents the economic sector, where a macroeconomic indicator (GDP/capita) and another of wealth distribution (GINI index) are considered to represent the economic power generated from agribusiness and its distribution to the regional population. Finally, the social sector is represented by the indicators of labor force (%) and income per capita (R$/person) from the donor side (S4), while the indicators human development index (HDI) and land conflicts (occurrence numbers/yr) represent society as a receiver (S5) of what is generated by MATOPIBA. Table 2 shows the meaning of each indicator, their units and objective of maximization or minimization, and the approach considered in establishing the goals for each indicator. Emphases should be done for K11 (emergy demand) indicator, because while some emergy experts suggest that emergy should be minimized since it is usually dependent on nonrenewable resources from nature and economy, other experts understand that emergy demand should be maximized to allow societal development under the lens of 'maximum empower' principle; this last perspective is considered in this work. All information provided by Table 2 is mandatory to run the goal programming philosophy, as presented in the next item. Data sources for each indicator are presented in Appendix A, allowing calculation verifications and reproduction wherever necessary.

*2.2.3. Stage #3 – Quantifying sustainability*

The chosen goals are based on well-established benchmarks, when available. For example, while for GINI and HDI indexes there are clearly criteria available for their measuring (both ranges from 0 to 1, GINI>0.4 means balanced income distribution and HDI>0.8 means high human development), for all other indicators there are no benchmarks available. The lack of available goals claims a way for estimating them before

**Table 2**
Indicators chosen to feed the 5SEnSU model.

| Sector | Indicator and unit | Meaning | Objective | Established goal |
|---|---|---|---|---|
| S1 | K11 – Emergy demand, in sej/ha yr | Total emergy (empower density) demanded by the MATOPIBA region | Maximize | Average for empower density (2007 as reference year) among the four Brazilian states that integrate MATOPIBA. |
| | K12 – Emergy loss, in sej/ha yr | Emergy loss by MATOPIBA due to soil erosion (organic matter) and due to natural forest loss (replaced by agribusiness expansion) | Minimize | Minimum value for emergy loss among 1990, 2000, 2010 and 2018, added to the standard deviation. |
| S2 | K21 – GHG emissions, in ton$CO_{2eq.}$/inhabitant yr | Greenhouse gases emissions due to agriculture, livestock, industrial processes, and waste management in MATOPIBA | Minimize | Minimum value for GHG emissions among 1990, 2000, 2010 and 2018, added to the standard deviation. |
| | K22 – Biodiversity loss, in species/yr | Biodiversity loss (in species) according to the loss of natural vegetation area in MATOPIBA | Minimize | Minimum value for biodiversity loss among 1990, 2000, 2010 and 2018. |
| S3 | K31 – GINI, dimensionless | Economic index that measures the degree of (in) equality of income distribution in MATOPIBA, ranging from 0 (complete equality) to 1 (complete inequality) | Minimize | Goal of 0.4 as suggested by the United Nation Organization as a balanced value for income distribution. |
| | K32 – GDP/capita, in R $/person | Gross domestic product is a macroeconomic index that represents economic activity. It was calculated by the yearly money generated in MATOPIBA, divided by its population | Maximize | Average for GDP/capita (2015 as reference year) among the four Brazilian states that integrate MATOPIBA. |
| S4 | K41 – Labor force, in % | Percentage of MATOPIBA's total population over 18 years old that are officially employed, independent of labor contract kind signed | Maximize | Average for labor force (2010 as reference year) among the four Brazilian states that integrate MATOPIBA. |
| | K42 – Income/capita, in R $/person month | Average of monthly income per capita of MATOPIBA's total population over 18 years old that are officially employed, independent of labor contract kind signed | Maximize | Average for income/capita (2010 as reference year) among the four Brazilian states that integrate MATOPIBA. |
| S5 | K51 – HDI, dimensionless | Human development index | Maximize | Goal of 0.8, which would classify |

(continued on next page)

**Table 2** (*continued*)

| Sector | Indicator and unit | Meaning | Objective | Established goal |
|---|---|---|---|---|
| | | | | MATOPIBA as having high human development index. |
| | K52 – Land conflicts, in number of conflicts | Occurrence of land conflicts officially registered in the MATOPIBA region. | Minimize | Minimum value for land conflicts among 1990, 2000, 2010 and 2018, added to the standard deviation. |

running the 5SEnSU model. For emergy demand, GDP/capita, labor force and income/capita that must be maximized, the criteria used was regional representativeness according to the average value for the states that integrate the MATOPIBA. This approach can be considered more realistic and/or practicable because real data representing the maximum actual capacity to achieve the performance for those indicators are considered. For emergy loss, GHG emissions, biodiversity loss, and land conflicts that must be minimized, goals that are more restrictive were established based on the minimum value found during the period studied (1990–2018). This approach represents the potential value that can be obtained by each indicator, in other words, once previously reached it can be reached again.

The 5SEnSU model is based on the philosophy of goal programming (Giannetti et al., 2019) rather than the traditional goal programming of maximization. Applying the philosophy of goal programming allows applying punishments for those indicators that are below or/and above the established goals. Punishments were established according to an individualist cultural perspective of analyst (Agostinho et al., 2019), in which a scenario of fossil fuel depletion is off the table. This cultural perspective was chosen because it is the most currently used approach by decision makers (usually with backgrounds in business administration and/or classical economy disciplines). Precisely, the punishments of 4.9 for the social sectors (S4 and S5), 2.3 for the environmental sectors (S1 and S2), and 1.8 for the economic sector S3 were set, based on the Eco-indicator 99 (Goedkoop & Spriensma, 2001) and further modified, used and available in Oliveira et al. (2016) and Agostinho et al. (2019). In regard to weighing factors that represent the relative importance of one indicator on another, equal importance is assumed for all indicators. Uncertainty analysis was not applied in this work due to lack of data, mainly because this study considers a temporal analysis of a region (which demands large amount of data) instead of a unique yearly diagnosis. Finally, the 5SEnSU model based on the philosophy of goal programming can be run through the modified Excel® spreadsheet (Supplementary Material A) based on the original one as developed by Giannetti et al. (2019).

*2.2.4. Stage #4 – Proposing improvements*

After running the 5SEnSU model for each studied year (1990, 2000, 2010 and 2018), the following indicators are obtained: (i) index of sustainability goal (ISG); (ii) sector sustainability indicator (SSI); (iii) sustainability synthetic indicator of system (SSIS). While the former represents the sustainability from each individual indicator after applying the normalizing, weighting, and punishment processes, the second one (SSI) represents the sustainability for 5SEnSU's sectors, and the third indicator (SSIS) represents the overall sustainability performance for MATOPIBA. From the different available ways to represent the obtained results, including tables, figures, and graphics, in this study the indicators SSI and SSIS are represented in a graphical form (bar graphics) to allow discussions and sustain conclusions aligned to the initial object of this study. The indicator ISG is not discussed because, although important for calculating the SSI and SSIS, it is not able to answer the research question supporting the development of this study.

Aiming to provide subsidies for public policies towards MATOPIBA development, a sensitivity analysis is applied on the ten chosen indicators that feed the 5SEnSU model. The procedure applied consists of increasing or reducing (which depends on the objective of maximizing or minimizing the indicator) the indicators individually by 5%, 10%, 15%, 20%, 25% and 30%, using 2018-year as reference, and maintaining constant all other nine indicators. These percentage values were set because, besides being usually considered in sensitivity analysis, indicator change up to 30% increase or reduction can be considered a real operational target to be implemented. This procedure is repeated, indicator by indicator, and a range of new SSIS values are obtained from simulations. In the end, a proposal for actions is provided according to the obtained SSIS values, pointing out which indicator should be prioritized to effectively implement public policies. A similar procedure was considered by Agostinho et al. (2019) and Johannesdottir et al. (2021).

Important to emphasize that the sensitivity analysis performed is based on a scenario evaluation to verify in what extend the outputs are affected by inputs; similar method was applied by Cellura et al. (2011) assessing uncertainties in life cycle assessments. None known mathematical or statistical model is applied, so instead of looking for a unique and optimal solution through goal programing techniques, risk analysis, among others, the idea is to provide a simple approach in obtaining quantitative data for decisions about where to concentrate efforts to achieve higher SSIS performance for the MATOPIBA region. An important aspect is regarded to existing dependence among indicators of Table 2, specifically GDP/capita with HDI and emergy demand with emergy loss; all other indicators are independent each other. To make the analysis simplest as possible, the dependencies between these two groups of indicators were disregarded. This assumption is acceptable for emergy demand & emergy loss dependency, since the later corresponds from 0.99 to 2.01% of emergy demand (Supplementary Material B). For the GDP/capita & HDI dependency, increasing GDP/capita will result in even better results for MATOPIBA's SSIS than setting HDI unchangeable (i.e. considering them as independent), since both indicators are modelled to be maximized. However, it is suggested future efforts to exclude the dependency issue between GDP/capita & HDI when applying the sensitivity analysis.

## 3. Results and discussions

### *3.1. The 5SEnSU-based sustainability indicators: a sectorial perspective of MATOPIBA*

After choosing the indicators, their objectives and goals supported by the logic behind the 5SEnSU conceptual model (Table 2), all indicators are quantified considering the spatial and temporal boundaries as predefined in Stage #1, as available in Appendix A. After gathering and subsequent standardization of primary data, the secondary data representing all chosen indicators are obtained as shown in Table 3, including individual indicator dynamics between 1990 and 2018, their objectives and goals. From that table, important aspects can be observed such as the increase across years for some indicators (emergy demand, biodiversity loss, GDP/capita, labor force, and income/capita, HDI), while others have a pulsing behavior (emergy loss, GHG emissions, GINI, and land conflicts). While increasing those indicators aimed at maximization can be seen as a positive aspect (e.g. emergy demand, GDP/capita, labor force, income/capita, and HDI), for those ones aimed at minimization such as biodiversity loss, the increase is seen as a negative behavior. It is interesting to note that while some indicators are below or above their established goals throughout the period studied (e.g. emergy demand, biodiversity loss, GINI, GDP/capita, labor force, income/capita, and HDI), other indicators have exceeded their goals (emergy loss, GHG emissions, and land conflicts), indicating the independence among indicators and complexity of the studied system.

**Table 3**
Individual indicator dynamics between 1990 and 2018, their objectives and goals.

| Sector | Indicator and unit [a] | 1990 | 2000 | 2010 | 2018 | Goal [b] | Objective[b] |
|---|---|---|---|---|---|---|---|
| S1 | K11 – Emergy demand, in E15 sej/ha yr | 4.33 | 4.37 | 4.51 | 4.67 | 9.61 | Maximize |
| | K12 – Emergy loss, in E13 sej/ha yr | 4.74 | 4.52 | 7.17 | 9.67 | 6.93 | Minimize |
| S2 | K21 – GHG emissions, in ton$CO_{2eq.}$/inhabitant yr | 14.1 | 16.8 | 14.9 | 10.5 | 13.2 | Minimize |
| | K22 – Biodiversity loss, in E7 species/yr | 3.16 | 5.24 | 5.56 | 7.52 | 3.16 | Minimize |
| S3 | K31 – GINI, dimensionless | 0.51 | 0.58 | 0.55 | 0.59 | 0.40 | Minimize |
| | K32 – GDP/capita, in R$/person yr | 908 | 2220 | 7954 | 10,538 | 14,681 | Maximize |
| S4 | K41 – Labor force, in % | 21.6 | 33.5 | 45.4 | 57.3 | 62.2 | Maximize |
| | K42 – Income/capita, in R$/person month | 109.42 | 155.92 | 280.17 | 339.98 | 465.16 | Maximize |
| S5 | K51 – HDI, dimensionless | 0.28 | 0.42 | 0.60 | 0.73 | 0.80 | Maximize |
| | K52 – Land conflicts, in number of conflicts | 45 | 18 | 200 | 272 | 140 | Minimize |

[a] Details available in Appendix A.
[b] Goals and objectives are described in Table 2.

According to Spera (2020), it is possible to increase agribusiness production without devastating natural vegetation, simply by applying appropriate cropping techniques such as double-cropping, using adapted seed cultivars, choosing those most agronomically suitable lands for intensive agriculture, and improving pasture lands. All these approaches focused on higher efficiency are characteristics of agribusiness producers that have access to information and economic investments, while the small-scale producers usually do not. Since large-scale productive systems are the ones that move or generate more financial resources and deeply affect regional economic performance, Table 3 shows improvement for macroeconomic indicators such as GDP/capita and income/capita. However, the problem is that the MATOPIBA region has large and wealthy agribusiness producers together with small producers based on specific cultural and economic characteristics. Favareto et al. (2019) argue that even with the increase of agricultural production for exportation, the poverty and economic inequality rates in MATOPIBA are still high, because there is a highly concentrated and specialized economic dynamic with low capacity to create jobs and strengthen local economic. This is consistent with the number of land conflicts and GINI index, but it is inconsistent with the labor force indicator that showed improvement during the studied period. Anyway, it is imperative that discourse on sustainability must consider a holistic perspective of MATOPIBA, as addressed in this present study. Although all these discussions supported by numbers in Table 3 are important to visualize the indicators dynamic behavior in MATOPIBA, nothing can be discussed regarding MATOPIBA's sustainability because the philosophy of goal programming based on the 5SEnSU model has not yet been applied.

After using the data presented in Table 3 to feed the Excell® file with the philosophy of goal programming (Supplementary Material A) as suggested by Giannetti et al. (2019), and running the software, the sustainability sector sustainability indicator (SSI) and sustainability synthetic indicator of system (SSIS) are calculated. According to Fig. 4 that shows the SSIs, different patterns and magnitudes can be observed during the 1990–2018 period, remembering that the highest SSI values means the worst sustainability performance. Two approaches are considered to discuss the results of Fig. 4: (i) focusing on the influence of sectors on the sustainability for different years, evaluated individually; (ii) focusing on the sectors behavior over the years. Focusing on SSIs influence on sustainability, the highest influence among the SSIs is due to S3 and S4 for 1990 and 2000. The year 2010 was mainly influenced by S2 and S3, while for 2018 the sectors S2 and S5 showed higher influence. The change on SSIs behavior becomes evident during the period, because while the social (as provider) and economic aspects showed the worst figures during the 90s, for the years 2010 and 2018 the worst performance is located in the environmental and social (as receiver) sectors. This indicates that agribusiness expansion in MATOPIBA over the years is improving the performance for macroeconomic and social (as a provider) aspects, while the environmental and social aspects (as a receiver) are getting worse. These results are consistent with the findings by Favareto (2019), who argues that MATOPIBA's macroeconomics improvement occurs thanks to greater income inequality and its impacts on society, combined with a larger environmental impact. Additionally, Ribeiro et al. (2020) point out that MATOPIBA presented a real GDP

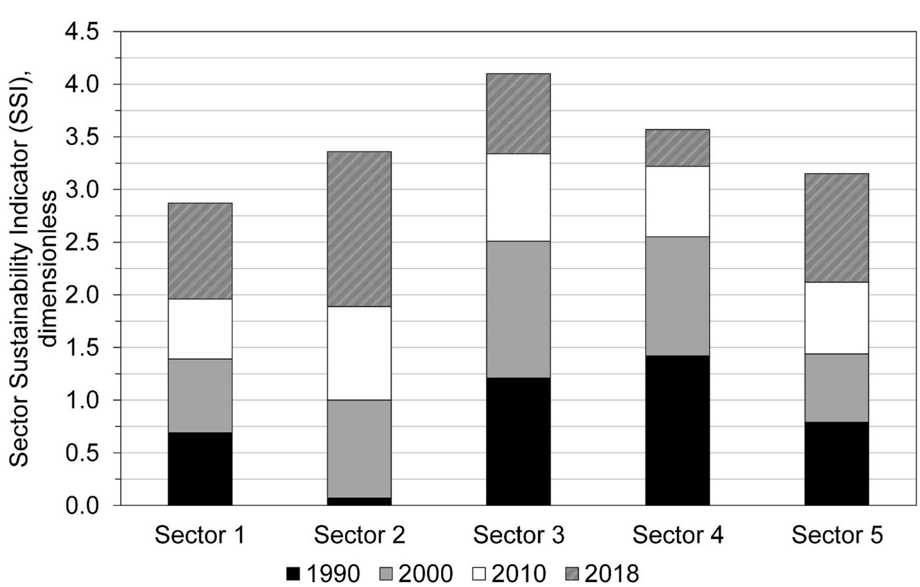


**Fig. 4.** Dynamics for sector sustainability indicator (SSI) between 1990 and 2018. SSI values from Appendix B.

growth rate of 5.1% per year over 2010–2015, a value higher than the Brazilian growth rate that achieved 1.5% in the same period. However, as previously discussed by Sá et al. (2015), the observed pulse of economic growth is associated with agribusiness, which usually is not appropriately considered to sustain or promote regional development in its full definition; in other words, the agribusiness in MATOPIBA generates macroeconomic growth, but not development.

Focusing on sector dynamics over the years, Fig. 4 shows a reduction - which means better performance – of SSI for sectors S3 and S4 in the period evaluated, indicating an improvement on performance for labor force, income/capita, GINI index and GDP/capita indicators. The S4 sector showed improvement for the SSI (from 1.42 in 1990 to 0.35 in 2018), indicating that agribusiness expansion over MATOPIBA is bringing benefits to society (as a provider); for S3, its SSI ranged from 1.21 in 1990 to 0.76 in 2018. According to Pereira (2019), there is huge heterogeneity inside MATOPIBA regarding socioeconomic issues, which is visibly reflected in the use of agricultural technologies. Large and productive agribusiness-based properties have a large amount and high quality (high-tech) equipment focused on agriculture precision, while small-managed family properties generally do not have access to high-tech equipment for agricultural production. While monoculture (mainly soybeans or cotton) is a feature of the former, polyculture supported by the federal government is a feature of the latter. On the other hand, the same author identified a slight reduction in technological inequality over 2006–2017, which is consistent with data in Fig. 4 that shows an improvement in the sustainability indicators of the economic and social sectors as a supplier (sectors S3 and S4) in 2010 and 2018.

The improvement in social (as a supplier) and economic aspects over years occurred at the same time that sectors S1, S2 and S5 got worse. The SSI of S2 (GHG emissions and biodiversity loss) is the one with highest variation, starting from 0.07 in 1990 to 1.47 in 2018, indicating a performance 21 times worse for the environment (as a receiver), which emphasizes this sector as the one most impacted by the agribusiness advancement in MATOPIBA. As for S1 and S5, Fig. 4 shows that variations were lower compared to all other sectors, showing that indicators representing these sectors were lower influenced than all other sectors (from 0.69 to 0.91 for S1 and from 0.65 to 1.03 for S5, with gradients of 0.22 and 0.38 respectively).

### 3.2. *The 5SEnSU-based sustainability indicators: a global perspective of MATOPIBA*

In general, the calculated SSIs show that while sector S2 got worse, and S3 and S4 were improved over the period of 1990–2018, the S1 and S5 performed better for intermediate years of 2000 and 2010. This complex behavior does not allow a clear and objective interpretation about the impact on sustainability as a result of agribusiness expansion in MATOPIBA, which claims for the calculation of the sustainability synthetic indicator of system (SSIS) to support more robust conclusions. Fig. 5 presents the MATOPIBA's SSISs, which reflects the inclusion of the chosen 10 indicators distributed on the five sectors of 5SEnSU model and after applying the goal programming philosophy. A non-linear behavior can be observed during the studied period, starting with 4.17 in 1990, getting worse in 2000 year with 4.71, improving for 2010 with 3.63, and getting worse again in 2018 with 4.51; the optimized value refers to the simulation approach as will be discussed in the next section. The worst performance for SSIS occurred in 2000, while the best one occurred in 2010. The observed random behavior for SSIS indicates that MATOPIBA's sustainability has not been increasing over the years, but neither can it be concluded that SSIS is decreasing. A statistical regression approach could be applied to obtain a model that would indicate an increase or decrease in the SSIS, but it is understood that the four-year sample as considered in this study could not be statistically representative, that is why a regression approach was not considered here, but it is suggested for future works.

The advance of agribusiness in MATOPIBA between 1990 and 2000 showed a decrease in regional sustainability (Fig. 5), mainly due to the biodiversity loss (ISG from 0.00 to 0.66; Appendix B) and GHG emissions (0.07–0.27) indicators, both belonging to sector S2 of the 5SEnSU model. The SSIS performance in this period could have been worse, but the labor force (ISG from 0.65 to 0.46) and HDI (0.65–0.48) indicators improved compared to 1990, counterbalancing the SSIS. This is a characteristic of the 5SEnSU model, in which the sustainability represented by the SSIS is the final expression of all the 10 indicators considered at once. In general, the period between 1990 and 2000 indicates a significant negative influence on the SSIS from the environmental sector (as a receiver), while the social sectors showed a positive influence. The economic and environmental sectors (as a provider) did not present significant influences.

Between 2000 and 2010, the agribusiness advancement in

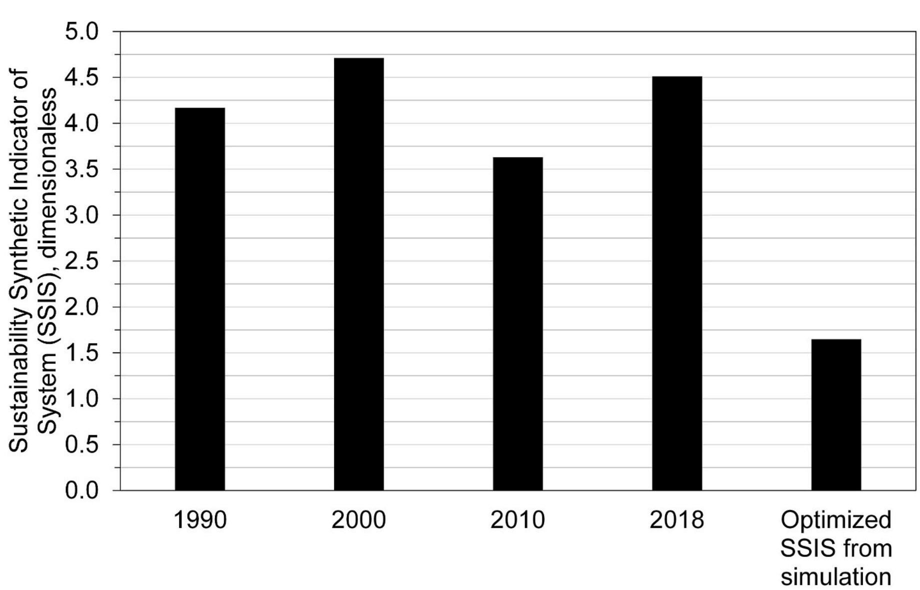


**Fig. 5.** Dynamics for sustainability synthetic indicator of system (SSIS) between 1990 and 2018 according to an individual analyst's cultural perspective. SSIS values from Appendix B. Optimized value is the result of sensitivity analysis as detailed presented in the next section.

MATOPIBA resulted in SSIS improvement (Fig. 5), mainly due to GDP/capita (ISG from 0.85 to 0.46; Appendix B), Income/capita (0.48–0.25), HDI (0.48–0.25), and to the Labor force (0.46–0.27). On the other hand, the worst performance obtained in the ISG for Land conflicts (0.18–0.43) prevented an even greater improvement for SSIS in the period. It is interesting to note that, in contrast with the period between 1990 and 2000, the economic and social sectors (as a provider) were the ones that most positively influenced the SSIS in the period between 2000 and 2010, with lower influence from the environmental and social sectors (as a recipient). Finally, between the period 2010 and 2018, Fig. 5 shows a performance decrease for SSIS as a result of agribusiness advancement in the MATOPIBA region. Indicators that negatively affected the most for SSIS were biodiversity loss (ISG from 0.76 to 1.38), land conflicts (0.43–0.94), and emergy loss (0.03–0.40), while those indicators that contribute positively for the SSIS were labor force (0.27–0.08), GDP/capita (0.46–0.28), and HDI (0.25–0.09). From a general view, and similar to the 1990–2000 period, the SSIS dynamics for 2010–2018 period showed that social (as recipient) and environmental sectors were the ones that negatively influenced SSIS, while the social sector (as provider) showed positive influence. The economic sector did not present significant influence.

According to Costanza (1999), a system can only be considered sustainable after a considerable period of observations, in which the predictions can be confirmed. If the analyzed period in this study of 28 years (1990–2018) can be assumed as sufficient to assess the dynamics of sustainability in the studied region, Fig. 5 shows that MATOPIBA obtained higher sustainability in 2010, reaching 3.63 for SSIS. If the behavior of the SSIS were decreasing throughout the analyzed period, it could be concluded that agribusiness advancement in MATOPIBA would lead to an increase in regional sustainability, but since the SSIS behavior is pulsing, an alternation between better and worse SSIS performances is observed. Returning to the research question supporting the development of this work (Does the advancement of agribusiness in the MATOPIBA region result in higher regional sustainability?), numbers from Fig. 5 do not provide robust elements for an accurate answer. On the other hand, Fig. 5 clearly indicates higher sustainability for 2010, followed by the years 1990, 2018 and 2000, respectively. The diagnosis developed in this study is of paramount importance to assist strategic plans for the agribusiness advancement in the MATOPIBA region, as it makes it possible to identify which variables led to the best performance in sustainability for 2010, and make efforts to replicate it.

### *3.3. Sensitivity analysis for strategic policy actions to increase MATOPIBA's sustainability*

As an important step in SUAPRO's procedure (Fig. 2), Stage #4 comprises the sensitivity analysis applied to the chosen 10 indicators considering 2018 as a baseline. This year was chosen because we seek to find the optimal SSIS value that could actually be considered as subsidies for public policies from a practical perspective, since it would not make sense to get an SSIS optimized for years prior to 2018, since it is the most recent year among those evaluated. Considering the Excel® spreadsheet containing the goal programming philosophy framework (Supplementary Material A), all simulations were performed resulting in those SSIS values presented in Table 4. From the 10 indicators considered in this study, 7 of them achieved higher performance by changing their value by 30% (increasing or decreasing depending on the objective), including emergy demand, emergy loss, biodiversity loss, GINI, GDP/capita, income/capita, and land conflicts. Two indicators achieved their best performance through 10% change (labor force and HDI), while one indicator (GHG emissions) showed that it is already at its best performance. These results are consequences of the initial established goals and indicators values for 2018 as shown in Table 3.

From the sensitivity analysis results of Table 4, one can observe the needed actions including maintaining, increasing, or decreasing the indicators in different percentages based on the 2018 values as a baseline to achieve the best SSIS performance. For example, the best SSIS performance of 3.80 would be achieved by reducing the biodiversity loss indicator by 30% and maintaining all other indicators unchanged, while the worst SSIS performance of 4.51 would be achieved by maintaining the current values for GHG emissions as for all other indicators. It is important to say that an ideal scenario would be reducing GHG emissions close to zero, but this study adopted goals that were understood as feasible to be achieved in a short and medium period of time, as explained in Table 2.

Since decision makers usually demand easy-to-understand information for effective decisions, the results of Table 4 can be summarized to provide a hierarchy for actions, from the one that would bring better results for SSIS to the one that would contribute the least. As presented in Table 5, to achieve the highest performance for MATOPIBA's sustainability, the first action to be taken should be a 30% reduction in the biodiversity loss indicator, which would result in an SSIS of 3.80, a value 0.71 lower than the 4.51 obtained in 2018, meaning higher performance. Potential difficulties on how to operationalize that 30% reduction in the biodiversity loss in practice are recognized, but these aspects are outside the scope of this present study.

As usually happens in practice during a decision implementation, even though it is recognized that a certain decision would bring higher benefits than another, it sometimes cannot be implemented due to other drivers such as lack of economic financing, lack of technological information, lack of specialized staff, lack of time for its execution, among others. Taking into consideration this practical issue, Table 5 indicates that the second option to increase MATOPIBA's sustainability would be a 30% reduction for the land conflicts indicator, which would result in an SSIS of 3.93; a value of 0.58 lower than the 4.51 obtained in 2018. Similarly, this sequential procedure is repeated to assist the decision maker, respecting the hierarchy of actions of Table 5. Different combinations could be achieved in scenarios where more than one indicator is simulated simultaneously and under different percentages of the suggested ones. Although not presented in this work, these different

**Table 4**
Sensitivity analysis for MATOPIBA's SSIS. Bold numbers with an (*) indicate the best performance from the simulation.

| Indicator | Objective | 2018 value for SSIS | Absolute values for SSIS according to objective of increasing or decreasing (value in parentheses shows the difference between the simulated with the original SSIS value) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 5% | 10% | 15% | 20% | 25% | 30% |
| K11 - Emergy demand | Increase | 4.51 | 4.49 (−0.02) | 4.46 (−0.05) | 4.44 (−0.07) | 4.42 (−0.09) | 4.39 (−0.12) | ***4.37* (-0.14)*** |
| K12 - Emergy loss | Reduce | 4.51 | 4.44 (−0.07) | 4.37 (−0.14) | 4.30 (−0.21) | 4.23 (−0.28) | 4.16 (−0.35) | ***4.13* (-0.38)*** |
| K21 - GHG emissions | Reduce | ***4.51**** | 4.53 (+0.02) | 4.55 (+0.04) | 4.57 (+0.06) | 4.58 (+0.07) | 4.60 (+0.09) | 4.62 (+0.11) |
| K22 - Biodiversity loss | Reduce | 4.51 | 4.39 (−0.12) | 4.28 (−0.23) | 4.16 (−0.35) | 4.04 (−0.47) | 3.92 (−0.59) | ***3.80* (-0.71)*** |
| K31 - GINI | Reduce | 4.51 | 4.44 (−0.07) | 4.37 (−0.14) | 4.29 (−0.22) | 4.22 (−0.29) | 4.14 (−0.37) | ***4.07* (-0.44)*** |
| K32 - GDP/capita | Increase | 4.51 | 4.48 (−0.03) | 4.44 (−0.07) | 4.41 (−0.10) | 4.37 (−0.14) | 4.33 (−0.18) | ***4.30* (-0.21)*** |
| K41 - Labor force | Increase | 4.51 | 4.47 (−0.04) | ***4.44* (-0.07)*** | 4.45 (−0.06) | 4.46 (−0.05) | 4.47 (−0.04) | 4.48 (−0.03) |
| K42 - Income/capita | Increase | 4.51 | 4.48 (−0.03) | 4.44 (−0.07) | 4.40 (−0.11) | 4.37 (−0.14) | 4.33 (−0.18) | ***4.29* (-0.22)*** |
| K51 - HDI | Increase | 4.51 | 4.47 (−0.04) | ***4.43* (-0.08)*** | 4.44 (−0.07) | 4.45 (−0.06) | 4.45 (−0.06) | 4.46 (−0.05) |
| K52 - Land conflicts | Reduce | 4.51 | 4.42 (−0.09) | 4.32 (−0.19) | 4.22 (−0.29) | 4.12 (−0.39) | 4.03 (−0.48) | ***3.93* (-0.58)*** |

**Table 5**
Action proposal hierarchy for public policies focused on MATOPIBA's SSIS improvement. Data from simulations presented in Table 4.

| Hierarchy for action | Indicator | Sector | Action | Indicator variation from 2018 values | Relative SISS improvement | SISS value after applying the action |
|---|---|---|---|---|---|---|
| 1st | Biodiversity loss | S2 | Reduce | −30% | −0.71 | 3.80 |
| 2nd | Land conflicts | S5 | Reduce | −30% | −0.58 | 3.93 |
| 3rd | GINI | S3 | Reduce | −30% | −0.44 | 4.07 |
| 4th | Emergy loss | S1 | Reduce | −30% | −0.38 | 4.13 |
| 5th | Income/capita | S4 | Increase | +30% | −0.22 | 4.29 |
| 6th | GDP/capita | S3 | Increase | +30% | −0.21 | 4.30 |
| 7th | Emergy demand | S1 | Increase | +30% | −0.14 | 4.37 |
| 8th | HDI | S5 | Increase | +10% | −0.08 | 4.43 |
| 9th | Labor force | S4 | Increase | +10% | −0.07 | 4.44 |
| 10th | GHG emissions | S2 | Maintain | 0% | 0.00 | 4.51 |

scenarios for SSISs can be easily simulated by using the Excel® spreadsheet containing the goal programming philosophy framework (Supplementary Material A).

Even though there are different options for scenario simulation, perhaps the most important one would be the 'optimized' scenario, in which all the proposed actions in Table 5 were successfully implemented. Using the Excel® spreadsheet were to run the suggested actions of Table 5, the 'optimized' SSIS would be 1.65. This value represents the maximum sustainability value – compared to the years 1990, 2000, 2010 and 2018 (Fig. 5) – that MATOPIBA could achieve according to the simulation criteria considered in this work. Focusing on the performance of the 5SEnSU sectors, the 'optimized' SSIS is the result of the following Sector Sustainability Indicators (SSIs): 0.38 for S1, 0.75 for S2, 0.10 for S3, 0.05 for S4, and 0.36 for S5 (Supplementary Material A). Comparatively, S2 is the sector that most negatively affects the 'optimized' SSIS, in which the biodiversity loss indicator with 0.67 for its index of sustainability goal (ISG) is the main driver.

After applying the sensitivity analysis, proposing the hierarchy for actions, and calculating the optimized SSIS value as a reference, the SUAPRO cycle (Fig. 2) is finalized. After this, a new diagnosis for a new cycle can be performed for the next year after implementing the changes into MATOPIBA towards higher sustainability. This continuous cycle is important to guarantee continuous improvements.

### 3.4. Limitations and suggestions for future efforts

As usual in any multicriteria approach, there is a certain degree of subjectivity in choosing indicators, goals, and setting importance or weights among them. The SUAPRO framework applied in this work seeks to reduce some uncertainties inherent in the goal programming philosophy as a multicriteria approach, and using the 5SEnSU model is a way to give epistemological solidity in choosing indicators that represent their respective sectors. In this present study, the choice of indicators to feed 5SEnSU was based on the authors expertise, as well as informal consultation with other experts, including information about the importance of indicators in representing the social, environmental and economic performance of regions (macro-scale), and on the availability of data for the different years evaluated (1990, 2000, 2010, and 2018). For future studies, a suggestion would be to consider other indicators such as water balance, identified by Spera et al. (2016) as an important variable resulting from the agribusiness advancement in MATOPIBA, or even land grabbing as suggested by Silva et al. (2023), a usual practice in that region.

The goals for each of the ten indicators (Tables 2 and 3) were carefully established to represent the regional reality, avoiding unattainable targets and considering tangible values in the short and medium periods of time, as it is understood that public policy implementation is based on these temporal scales. In any case, one could consider setting goals through participatory meetings in which groups of experts would be consulted, including experts from agribusiness companies, public authorities, traditional communities and even the university faculty as a representative of the scientific field. This participative approach would also be applied in establishing weights or punishments for the indicators feeding the 5SEnSU model; all ten indicators were considered with equal importance in the present study to represent MATOPIBA's sustainability.

The quantity and quality of data available to feed the SUAPRO procedure is a limiting factor for the development of this study, and it is important to emphasize that the most reliable and most historically accurate data were used in this study. Going forward, a suggestion would be to continue this study considering the years after 2018, which would result in larger amount of data to statistically represent MATOPIBA's SSIS dynamics, and very probably answer the initial research question of this study with statistical robustness. Choosing indicators that are independent each other is other important issue to guarantee more accurate results from the sensibility analysis.

Finally, the inclusion of additional drivers in the SSIS simulations to subsidize a hierarchy of actions to be implemented by the decision maker is suggested for the future. Variables that would act as limiting factors for the execution of a certain action, such as implementation cost and execution time, could be included to find an optimal and practically feasible combination of public policies to achieve higher sustainability for the MATOPIBA region.

## 4. Conclusions

Focusing on the performance of MATOPIBA's sectors under the 5SEnSU model, social and economic sectors showed lower performance than the environmental sector during the 1990–2010 period, as represented by the sector sustainability indicator (SSI). An opposite behavior occurs during the subsequent period of 2010–2018, in which the environmental sector showed lower performance. This indicates that while MATOPIBA's macroeconomic and social (as the provider function) sectors are achieving better performances for sustainability over the years during agribusiness expansion, the environmental and social (as the receiver function) sectors are obtaining lower performance.

Focusing on the MATOPIBA as a whole, the sustainability synthetic indicator of system (SSIS) showed a pulsing behavior over years, achieving 4.17 in 1990, 4.71 in 2000, 3.63 in 2010, and 4.51 in 2018. The best sustainability performance for MATOPIBA was in 2010. The pulsing behavior observed for the MATOPIBA's SSIS during the 1990–2018 period does not allow the conclusion that agribusiness expansion is affecting negatively, or even positively, the performance of MATOPIBA's sustainability.

As for public policy suggestions, the top three actions include reducing biodiversity loss, land conflicts and GINI indicators by 30% compared to their values in 2018. Accomplishing all ten suggested actions, MATOPIBA's SSIS would achieve the maximized performance of 1.65.

Additional efforts should focus on gathering more data to calculate the SSISs for MATOPIBA after 2018 that, under statistic validation, would answer whether the agribusiness expansion on MATOPIBA results in higher or lower regional sustainability.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apgeog.2023.103080.

## Appendix A. Data source by indicator

| Indicator | Data source |
|---|---|
| K11 – Emergy demand, in sej/ha yr | Emergy calculation based on Odum (1996) with baseline of 12.00E24 sej/yr. Calculation details available in Supplementary Material B. MATOPIBA's land use (in hectares) obtained from MAPBIOMAS (2019). |
| K12 – Emergy loss, in sej/ha yr | Emergy loss includes soil and natural vegetation items. (i) For calculating the emergy of soil loss (organic matter), the works of Brandt-Williams (2002), Shah et al. (2019), and Cavalett and Ortega (2010) were considered as references. Emergy calculations for soil loss are available in Supplementary Material B. (ii) For calculating the emergy of natural vegetation areas lost during studied years, the hectares lost were obtained from MAPBIOMAS (2019), while the empower density of Savannah (4.50E14 sej/ha yr; Venezuela case) from Brown and Bardi (2001) was considered. Natural vegetation lost of 1.88E05 $ha_{forest}$, 3.12E05 $ha_{forest}$, 3.31E05 $ha_{forest}$, and 4.48E05 $ha_{forest}$ for 1990, 2000, 2010 and 2018 years respectively. Total area of MATOPIBA is 7.32E07 $ha_{total}$. Calculation = ($ha_{forest}$) (sej/ha yr)/$ha_{total}$. Summing (i) and (ii), the K12 indicator is 4.74E13 sej/ha yr for 1990, 4.52E13 sej/ha yr for 2000, 7.17E13 sej/ha yr for 2010, and 9.67E13 sej/ha yr for 2018. |
| K21 – GHG emissions, in $tonCO_{2eq.}$/inhabitant yr | Greenhouse gases emissions for municipalities within the MATOPIBA region in $tonCO_{2eq.}$/yr were obtained from SEEG (2019), which uses the GWP-AR5 method. Total MATOPIBA's emissions is obtained by summing municipal emissions, and then divided by total MATOPIBA's population of 6.3 millions inhabitants. Emissions from agricultural and livestock production, energy, industrial processes, and from waste were included. Final numbers are 14.1 $tonCO_{2\text{-}eq.}$/inhabitant for 1990, 16.8 $tonCO_{2\text{-}eq.}$/inhabitant for 2000, 14.9 $tonCO_{2\text{-}eq.}$/inhabitant for 2010, and 10.5 $tonCO_{2\text{-}eq.}$/inhabitant for 2018. |
| K22 – Biodiversity loss, in species/yr | Natural vegetation areas (in $ha_{forest}$/yr) lost during years from MAPBIOMAS (2019), while the biodiversity value in species per hectare (168 species/$ha_{forest}$) was obtained from IFN (2022). Natural vegetation lost of 1.88E05 $ha_{forest}$, 3.12E05 $ha_{forest}$, 3.31E05 $ha_{forest}$, and 4.48E05 $ha_{forest}$ for 1990, 2000, 2010 and 2018 years respectively. |
| K31 – GINI, dimensionless | GINI index for each municipality within MATOPIBA obtained from PNUD (2020) for 1990–2018 years. An average value was calculated to represent MATOPIBA's GINI. |
| K32 – GDP/capita, in R$/person | GDP for MATOPIBA's municipalities obtained from IBGE (2020) and IPEA (2019) for 1990–2018 years. An average value was calculated to represent MATOPIBA's GINI. The goal for this indicator considers the average GDP/capita (2015 as reference year) for the four states that integrate MATOPIBA region, resulting in 14,681.16 R$/capita yr. |
| K41 – Labor force, in % | Labor force for each municipality within MATOPIBA obtained from IBGE (2017) for 1990–2018 years. An average value was calculated to represent MATOPIBA's Labor force. The goals for this indicator is assumed as the average for labor force (2010 as reference year) among the four Brazilian states that integrate MATOPIBA. |
| K42 – Income/capita, in R$/person month | Values for each municipality within MATOPIBA obtained from PNUD (2020). An average value was calculated to represent MATOPIBA's income/capita. Goal established as the average income/capita value for Maranhão state (360.34 R$/capita month), Tocantins state (586.62 R$/capita month), Piauí state (416.93 R$/capita month), and Bahia state (496.73 R$/capita month), data from PNUD (2020). |
| K51 – HDI, dimensionless | HDI index for each municipality within MATOPIBA obtained from PNUD (2020) for 1990–2018 years. An average value was calculated to represent MATOPIBA's HDI. |
| K52 – Land conflicts, in number of conflicts | Land conflicts in MATOPIBA obtained directly from Pastoral Commission for the Land (CPT, 2017) for 1996, 2000, 2010 and 2016 as reference years due to data availability. |

## Appendix B. Index of Sustainability Goal (ISG), Sector Sustainability Indicator (SSI) and Sustainability Synthetic Indicator of System (SSIS) for MATOPIBA during 1990, 2000, 2010 and 2018 years. Data from Supplementary Material A

| Indicator by sector | 1990 | | | 2000 | | | 2010 | | | 2018 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ISG | SSI | SSIS | ISG | SSI | SSIS | ISG | SSI | SSIS | ISG | SSI | SSIS |
| Sector S1 | – | 0.69 | – | – | 0.70 | – | – | 0.57 | – | – | 0.91 | – |
| K11 | 0.55 | – | – | 0.55 | – | – | 0.53 | – | – | 0.51 | – | – |
| K12 | 0.14 | – | – | 0.15 | – | – | 0.03 | – | – | 0.40 | – | – |
| Sector S2 | – | 0.07 | – | – | 0.93 | – | – | 0.89 | – | – | 1.47 | – |
| K21 | 0.07 | – | – | 0.27 | – | – | 0.13 | – | – | 0.09 | – | – |
| K22 | 0.00 | – | – | 0.66 | – | – | 0.76 | – | – | 1.38 | – | – |
| Sector S3 | – | 1.21 | – | – | 1.30 | – | – | 0.83 | – | – | 0.76 | – |
| K31 | 0.28 | – | – | 0.45 | – | – | 0.38 | – | – | 0.48 | – | – |
| K32 | 0.94 | – | – | 0.85 | – | – | 0.46 | – | – | 0.28 | – | – |
| Sector S4 | – | 1.42 | – | – | 1.13 | – | – | 0.67 | – | – | 0.35 | – |
| K41 | 0.65 | – | – | 0.46 | – | – | 0.27 | – | – | 0.08 | – | – |
| K42 | 0.76 | – | – | 0.66 | – | – | 0.40 | – | – | 0.27 | – | – |

(continued on next page)

(*continued*)

| Indicator by sector | 1990 | | | 2000 | | | 2010 | | | 2018 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ISG | SSI | SSIS | ISG | SSI | SSIS | ISG | SSI | SSIS | ISG | SSI | SSIS |
| Sector S5 | – | 0.79 | – | – | 0.65 | – | – | 0.68 | – | – | 1.03 | – |
| K51 | 0.65 | – | – | 0.48 | – | – | 0.25 | – | – | 0.09 | – | – |
| K52 | 0.14 | – | – | 0.18 | – | – | 0.43 | – | – | 0.94 | – | – |
| Global | – | – | 4.17 | – | – | 4.71 | – | – | 3.63 | – | – | 4.51 |

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