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Sustainability Assessment supported by Geographic Information System: challenges, opportunities and application

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Sustainability Assessment supported by Geographic Information System: challenges, opportunities and application

Thesis presented to the Multidisciplinary Doctoral Program in Environmental Sciences (CIAMB), of the Pro-Rectory of Research and Graduate Studies at the Federal University of Goiás (UFG), as a partial requirement for obtaining the degree of Doctor in Environmental Sciences.

Concentration Area: Environmental Structure and Dynamics

Advisor: Prof. Dr. Denilson Teixeira

Co-advisor: Lucia Rocchi, PhD

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Ficha de identificação da obra elaborada pelo autor, através do Programa de Geração Automática do Sistema de Bibliotecas da UFG.

ATA DE DEFESA

AGRADECIMENTOS

Essa tese de doutorado é composta por produtos científicos frutos de muito trabalho. Aqui estão incluídas algumas discussões em sala de aula, ainda no âmbito do cumprimento dos créditos necessários para o doutoramento, inúmeras discussões em ambientes virtuais, em virtude das necessárias restrições impostas pelo período da pandemia da COVID-19, com muito diálogo com professores e pesquisadores de diferentes partes do mundo.

É dessa forma que quero iniciar os meus agradecimentos, enfatizando que essa tese de doutorado somente pôde ser construída porque muitas mãos e mentes fizeram parte, não somente do produto final, mas também da minha caminhada de formação científica.

Assim, eu inicio agradecendo ao meu orientador, Prof. Dr. Denilson Texeira, que com muita paciência, sabedoria, e admirável generosidade, me conduziu por essa jornada apontando as direções necessárias para além do desenvolvimento dessa pesquisa, mas abrangendo e impactando o meu crescimento pessoal.

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Ao Prof. Dr. Antonio Boggia, que, ao receber um simples email enviado por um estudante de doutorado do sul global, não apenas demonstrou disponibilidade em compartilhar seus conhecimentos, como abriu as portas da Universtà degli Studi di Perugia na Italia, e me inseriu no convívio de seletos pesquisadores daquela instituição por um período de sete meses.

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Mas essa tese não foi construída “apenas” por mãos e mentes científicas, mas também por corações e almas generosas.

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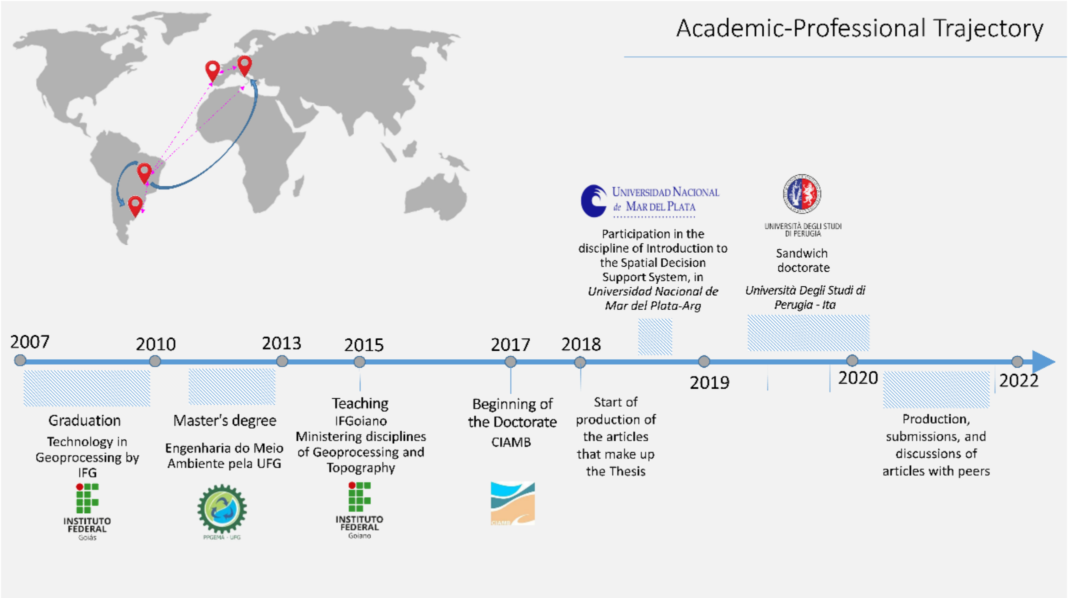
Por fim, e talvez o mais importante dos agradecimentos, ao meu filho Victor Tomaz Freitas Filho. Por quase todos esses anos que compreendem o doutorado, estivemos só nos dois, e por muitas vezes eu faltei, mesmo estando a um cômodo de distância. Obrigado por compreender e ter a grandeza de apoiar.

ACADEMIC-PROFESSIONAL TRAJECTORY

In the illustration below, I detail my path of professional and academic training.



I am a Technologist in Geoprocessing, graduated from the Federal Institute of Education, Science and Technology of Goiás (IFG), where I entered in 2007 and concluded the course in 2010. At graduation, I obtained an affinity for the exact disciplines, and in the common core of Geomatics I identified myself with the disciplines of Cartography, Geographic Information System, Remote Sensing, Topography, and Geodesy.

In 2011, I joined the Strictu Senso Graduate Program in Environmental Engineering at the School of Civil Engineering at the Federal University of Goiás (PPGEMA-UFG), working in the line of research called Environmental Sanitation and Water Resources. Still in 2011, concurrently with completing the master's credits, I started teaching activities in private colleges in Goiânia, teaching Topography and Geoprocessing.

In 2015, through the selection process, I was approved as an effective exclusive dedication teacher at the Urutaí Campus of the Federal Institute of Goiano, assigned to the School of Agricultural Engineering and teaching Topography subjects for technical and higher courses, in addition to Geoprocessing subjects only for higher courses.

In March 2017 I started my doctorate at the Graduate Program in Environmental Sciences (CIAMB) of the Pro-Rectory of Research and Graduate Studies at the Federal University of Goiás (PRPPG - UFG), a concentration area called Environmental Structure and Dynamics. From then on, I started to participate in disciplines that involved the development of the thesis, as well as scientific approaches in interdisciplinary disciplines. In addition, I started my collaborative participation in the Sustainability Group. It is a study and research group formed by researchers, created with the objective of mutual improvement of the scientific training process of the participants. There, I had the opportunity to directly and indirectly monitor and assist works of different scopes, resulting in co-authorship of articles.

From the first results, it was evident that the need to specialize in other areas of knowledge would be of fundamental importance for the good development of the thesis. So, in October 2018, I took part in a course called Problems of Decision in the Management of Natural Resources: Introduction to multicriteria analysis (MCA) and spatial decision support systems (SDSS), at the *Facultad de Ciencias Exactas y Naturales* of the *UNIVERSIDAD NACIONAL DE MAR DEL PLATA*, in Argentina, passing the final evaluation of the course with concept nine.

Participation in that discipline was essential not only to generate new knowledge that could be used in writing the thesis, but also to start the process of forming an international scientific cooperation network that would be expanded later.

Thus, new challenges arose during the development of the work, especially in the process of evolution of the first article, which now pointed to new international horizons from the identification of a research group from the *Dipartimento di Scienze Agrarie, Alimentari ed Ambientali*, in the nucleus of Applied Economics, from the *UNIVERSITÀ DEGLI STUDI DI PERUGIA*, in the city of Perugia, Italy. After a remote presentation and a demonstration of interest in carrying out a brief internship with the group's members, I received an invitation letter from Prof. Doctor Antonio Boggia, and so I started to develop part of the thesis under the supervision of experienced researchers in the use of multicriteria evaluation models integrated into the Geographic Information System, in particular for the application of sustainability indicators (SI).

The realization of this sandwich doctorate process comprised the period from August 2019 to March 2020, and resulted in an expansion of the scientific cooperation network initiated in Argentina, in addition to the formalization of the co-orientation of the thesis with Lucia Rocchi, Ph.D.

From then on, a long process began, but was extremely edifying, of writing the articles with the direct participation of the advisor, co-adviser, members of the qualification committee, colleagues in the research group composed of students from CIAMB and other programs, and with reviewers from different journals to which the articles were submitted.

ABSTRACT

Oliveira, Victor Tomaz de. **Sustainability Assessment supported by Geographic Information System: challenges, opportunities, and application**. 2022. XX f. Doctoral thesis (PhD in Environmental Sciences) – Graduate Program in Environmental Sciences, Federal University of Goiás, Goiânia-GO, 2022.

This doctoral thesis aims, in general, to identify the theoretical bases and methodological guidelines for an assessment of sustainable development supported by Geographic Information Systems (GIS), as well as to point out the recurrent challenges of its application. To achieve this goal, a series of four surveys was developed based on bibliographic and bibliometric reviews and the use of geospatialized tools and products. In the first study, we realized that GIS-supported SA address sustainability mainly from an ecological perspective and that methodologically rely mainly on the use of remote sensing techniques and multicriteria decision analysis, mostly at subnational levels. In the second, we identify the main driving themes and the trend in the multidimensionality of the evaluations, guided by global sustainability goals. In the third study, we reveal some main challenges related to evaluation processes at the regional level, contextualizing the spatialization of data and processes. In the fourth and last study, we broaden the discussion of the SA approach on a regional scale, proposing and applying a comprehensive spatial decision support system, generating a performance index towards sustainability for a Brazilian metropolitan region, using transparent mathematical models and a set of flexible variables. In general, these results suggest the use of GIS to fill important gaps at different stages of the SA process.

Keywords: Geographic information systems, sustainable assessment, bibliometric, SSAM, regional sustainability.

FIGURE LIST

Figure 2.1 Visual abstract. 7

Figure 2.2 Infographic of the research steps. 12

Figure 2.3 Sustainability Context. Adapted from Alfredo et al. (2018) and Patterson et al. (2017). 13

Figure 2.4 Distribution of the indexed research corpus and citations from 1990 to 2020. 15

Figure 2.5 Authors' co-citation network. 18

Figure 2.6 Referral co-citation network. 19

Figure 3.1 Methodological steps. 40

Figure 3.2 Most frequent keywords. 43

Figure 3.3 Thematic maps of keywords 1990–2020. 44

Figure 3.4 Map of behavior and thematic evolution. 47

Figure 4.1 Schematic composition of the core set of indicators 66

Figure 5.1 SD Goals, targets and dimensions contemplated. 91

Figure 5.2 Maps of the seven dimensions: a) Education Index, b) Employment Index, c) Environmental Index, d) Equality Index, e) Health Index, f) Services Index and g) Well-being Index. 93

Figure 5.3 General Performance Index towards Sustainability, by municipality of the Metropolitan Region of Goiânia. 95

Figure 5.4 Scatter plot: Gross domestic product (Reais per capita) and General Performance Index towards Sustainability 98

Figure 5.5 Scatter plot: Municipal Performance Index and General Performance Index towards Sustainability. 100

TABLE LIST

Table 1.1 Theoretical and methodological matrix of studies. Adapted from Ramos et. al. (2019). 4
Table 1.2 Identification and characteristics of documents related to the studies. 5
Table 2.1 Top journals. 15
Table 2.2 Main authors. 17
Table 3.1 Quantification and characterization of keywords 1990–2020. 45
Table 5.1 Reference of publications that contributed to the selection of indicators. 87
Table 5.2 Sources consulted to collect secondary data. 89
Table 5.3 Weights 92
Table 5.4 Back analysis: some examples 96
Table 5.5 Sensitivity analysis: results 96
Table 5.6 Methodological information for each indicator. 106
Table 6.1 Matrix of individualized conclusions. 113

CONTENTS

1 GENERAL INTRODUCTION..1

1.1 THESIS STRUCTURE AND A BRIEF DESCRIPTION OF THE STUDIES.....................................2
1.2 REFERENCES 6

2 TRENDS IN SUSTAINABILITY ASSESSMENT SUPPORTED BY GEOGRAPHIC INFORMATION SYSTEMS: A BIBLIOMETRIC APPROACH.........7

2.1 INTRODUCTION 8
2.2 MATERIAL AND METHODS..9
2.3 RESULTS 13
2.3.1 Characterization of the knowledge domain..14
2.3.2 Knowledge Structure..17
2.4 DISCUSSION 20
2.4.1 Further remark about the intellectual structure and knowledge domain......................22
2.5 CONCLUSIONS..24
2.6 STUDY LIMITATIONS/STRENGTHS 25
2.7 REFERENCES 26

3 GEOGRAPHIC INFORMATION SYSTEM APPLIED TO SUSTAINABILITY ASSESSMENTS: CONCEPTUAL STRUCTURE AND RESEARCH TRENDS...........34

3.1 INTRODUCTION 34
3.2 BACKGROUND..36
3.3 MATERIALS AND METHODS 39
3.4 RESULTS 42
3.4.1 Knowledge Structure..43
3.5 DISCUSSION 46
3.6 CONCLUSIONS..49
3.7 STUDY LIMITATIONS/STRENGTHS..50
3.8 REFERENCES 50

4 OPERATIONALIZING THE REGIONAL SUSTAINABILITY ASSESSMENT BY INDICATORS 56

4.1 INTRODUCTION 56
4.2 SUSTAINABILITY: A MULTIDIMENSIONAL CONCEPT..58
4.3 MULTIDIMENSIONALITY THAT FAVORS ASSESSMENT 60
4.4 REGIONAL SUSTAINABILITY ASSESSMENT: OPERATIONAL CHALLENGES 62
4.5 RSA OPERATIONAL GAPS AND METHODOLOGICAL PATHWAYS 63
4.5.1 Multilevel Interaction in the RSA..63
4.5.2 Stakeholder participation in RSA..66
4.5.3 Geospatial Approach in the RSA 67
4.6 FINAL REMARKS..72
4.6.1 Research Limitations..73

4.6.2 Gaps That Persevere......73
4.7 REFERENCES......74

5 PERFORMANCE TOWARDS SUSTAINABILITY: A REGIONAL ASSESSMENT SUPPORTED BY THE GIS......78

5.1 INTRODUCTION......78
5.2 MATERIALS AND METHODS......80
5.2.1 The scope of the framework......80
5.2.2 Steps and methods of framework construction......81
5.3 RESULTS AND DISCUSSION......86
5.3.1 The challenges in the selection and instrumentalization of indicators in the context of the 2030 Agenda......86
5.3.2 Weighing, spatialized index generation and back analysis......92
5.3.3 Complementary analysis for the GPIS used for the Metropolitan Region of Goiânia.97
5.4 CONCLUSION......101
5.5 STUDY LIMITATIONS/STRENGTHS......102
5.6 REFERENCES......102
5.7 SUPPLEMENTARY MATERIAL......106

6 FINAL CONSIDERATIONS......110

1 GENERAL INTRODUCTION

There are numerous types and approaches for existing Sustainability Assessments (SA). Over the last three decades, a number of frameworks, tools, and models have been developed to conceptualize, operationalize, and measure the Sustainable Development (SD) progress of various systems. However, this is not an easy task considering the diversity of conceptualizations and interpretations inherent in the term “sustainability” (PATTERSON, 2017).

Furthermore, the number of methods and tools to assess and report DS is immensely greater if we consider scientific publications that try to fill some of the gaps that still persist in this field of research. Among the main instruments, the use of Sustainability Indicators (SI) has been the most popular to translate SA, either from a set of indicators or through an aggregated result (RAMOS, 2019).

To exemplify, we cite Singh (2009) who provided, through a review, an overview of 70 different aggregated sustainability indices that have been applied in policy practice. In common is the use of variables that try to represent some human activity (or its reflection), mainly in the social, economic, or environmental fields. However, in most of the evaluations addressed by Singh, these variables are related to only one of these aspects, while new perspectives indicate a broader view, in which these dimensions are addressed in an integrated way (United Nations, 2015). This indicates that the assessment processes differ as the interpretation of sustainability also diversifies. In this perspective, new challenges are imposed on evaluators, giving rise to different proposals for evaluation models, as well as tools capable of supporting the evaluation process.

In their review work, Olawumi and Chan, (2018) find that future studies on sustainability research topics tend to apply some innovative technologies, including Geographic Information Systems (GIS). If, on the one hand, this finding indicates an expectation in the sense of overcoming some obstacles relevant to SA, on the other hand, it raises concerns about the new challenges that may arise inherent to its applicability. In general, a main question arises that needs to be answered, namely: How can a Geographic Information System act in the Sustainability Assessment processes?

This question is as important as it is broad. This is because, to answer it, it is first necessary to position the SA supported by GIS within the extensive sustainability debate. From then on, it becomes possible to unveil the conceptual framework of this field of research, in addition to revealing the methodological paths that can guide the evaluation process for an adequate use of the tool.

That said, this doctoral thesis aims, in general, to identify the theoretical bases and methodological guidelines for SA supported by GIS. Taking into account the results to be achieved, we also aim to propose an SA framework and point out the opportunities and challenges of its GIS-based application.

1.1 Thesis structure and a brief description of the studies.

This research seeks to achieve these objectives based on bibliographic and bibliometric reviews and the use of geospatialized tools and products and is organized as follows. After the General Introduction, where the research topic is problematized, two bibliometric reviews are presented. The first (Section 2) brings together 1700 articles selected from a structured search in the Scopus database, and a descriptive analysis is carried out characterizing the knowledge domain of this field of research, in addition to an in-depth debate based on the structure of knowledge obtained by network analysis and clustering of co-citation of authors and references. The second (Section 3) is presented as a complement to the first, where patterns and trends, theoretical and methodological, are explored in SA works supported by GIS. After a few rounds of discussion with peers, the search patterns were updated, expanding to 1721 articles, with discussions that developed from the characterization of the conceptual structure through the relationship network found by the co-occurrence of the keywords. In addition to the guidance of Dr. Denilson Teixeira, these studies were co-supervised by Dr. Lucia Rocchi, in collaboration with Dr. Antonio Boggia, both professors and researchers in the Department of Agricultural, Food, and Environmental Sciences of the University of Perugia, Italy.

Next (Section 4), the study presents a bibliographic review where different particularities of SA are presented and discussed on a regional scale, as it is an important characteristic of SA supported by GIS identified in the previous sections. Here, some of the main gaps and operational challenges to consider for effective assessments where the spatial dimension is integrated were highlighted. This study was guided by Dr. Denilson Teixeira in collaboration with Dr. André Cavalcante da Silva Batalhão, research associate at the Center for Environmental and Sustainability Research (CENSE), School of Science and Technology, Universidade Nova de Lisboa – Portugal.

The fourth and last study that makes up this thesis (Section 5) presents the proposition and application of a SA framework on a regional scale based on GIS techniques and products. In this study, we approach the stages of defining the scope of the framework, selection and instrumentation of indicators, weighing, aggregation, sensitivity and additional analysis of the results obtained in a Brazilian metropolitan region. This study was carried out in collaboration with Dr. Denilson Teixeira. Dr. Lucia Rocchi and Dr. Antonio Boggia.

Finally, in Section 6 we highlight the final considerations in which the main contributions to knowledge are highlighted, where new frontiers are opened for future research. We also emphasize that this doctoral thesis is composed of original and review scientific articles, in addition to a book chapter, and that these articles were produced from the scope of different scientific journals. In Table 1.1, we present a theoretical and methodological matrix to link studies, identifying them by titles, research questions, objectives, and methods. In Table 1.2, information about the journals in which they were submitted and published is listed, when applicable.

Table 1.1 Theoretical and methodological matrix of studies. Adapted from Ramos et. al. (2019).

<table>
<tr><td colspan="4">CENTRAL RESEARCH QUESTION
How can a Geographic Information System (GIS) act in the Sustainability Assessment (SA) processes?</td></tr>
<tr><td colspan="4">GENERAL OBJECTIVE
Identify the theoretical bases and methodological guidelines for SA supported by GIS, as well as point out the challenges in its application.</td></tr>
<tr><td rowspan="2">Title of each study</td><td colspan="3">JUSTIFICATION OF DISTINCTION</td></tr>
<tr><td>Research question</td><td>Main objective</td><td>Methods</td></tr>
<tr><td>Trends in sustainability assessment supported by geographic information systems: a bibliometric approach</td><td rowspan="2">What are the patterns and trends, theoretical and methodological, in SA supported by GIS?</td><td>Identify what approaches to sustainability are used by GIS-supported SA work</td><td>Bibliometric review:
Descriptive data and
Intellectual structuring</td></tr>
<tr><td>Geographic information system applied to sustainability assessments: conceptual structure and research trends</td><td>Understand in a more holistic way the thematic fields in which geospatial tools act in the evaluations that aim to measure sustainability</td><td>Bibliometric review:
Conceptual structuring</td></tr>
<tr><td>Operationalizing the regional sustainability assessment by indicators</td><td>What are the operational gaps and methodological paths of SA supported by GIS on a regional scale?</td><td>To discuss different operational particularities of the Regional Sustainability Assessment, pointing out methodological paths to overcome challenges that we consider essential in the operationalization of the evaluation and that aim to fill some identified gaps in the area</td><td>Bibliographic review</td></tr>
<tr><td>Performance towards sustainability: a regional assessment supported by the GIS</td><td>What are the challenges of applying a multidimensional SA based on GIS on a regional scale?</td><td>To broaden the discussion on the approach of SA on regional scales, proposing and applying a geospatialized performance assessment framework towards Sustainability</td><td>Multicriteria Spatial Decision Support Systems
by Spatial Sustainability Assessment Model (SSAM)</td></tr>
</table>

Table 1.2 Identification and characteristics of documents related to the studies.

Title of the study	***Kind of study***	***Intended journal***	***Journal metrics***	***Publication Status***	***DOI***
Trends in sustainability assessment supported by geographic information systems: a bibliometric approach	Review	Environmental Science & Policy	CiteScore 10 Impact factor 6.424	Submitted Second round of discussions	Not apply
Geographic information system applied to sustainability assessments: conceptual structure and research trends	Review	ISPRS International Journal of Geo-Information	CiteScore 5.0 Impact factor 3.099	Published on 16/11/2022	https://doi.org/10.3390/ijgi11110569
Operationalizing the regional sustainability assessment by indicators	Review	Book: The Route Towards Global Sustainability: Challenges and Management Practices. Springer Publisher	Not apply	In press	ISBN978-3-031-10436-7 https://doi.org/10.1007/978-3-031-10437-4_4
Performance towards sustainability: a regional assessment supported by the GIS	Article	Land Use Policy	CiteScore 9.9 Impact factor 6.189	Submitted	Not apply

1.2 References

Olawumi, T. O., & Chan, D. W. M. (2018). A scientometric review of global research on sustainability and sustainable development. *Journal of Cleaner Production*, *183*, 231–250. https://doi.org/10.1016/j.jclepro.2018.02.162

Patterson, M., Mcdonald, G., & Hardy, D. (2017). Is there more in common than we think? Convergence of ecological footprinting , emergy analysis , life cycle assessment and other methods of environmental accounting. *Ecological Modelling*, *362*, 19–36. https://doi.org/10.1016/j.ecolmodel.2017.07.022

RAMOS, Heidy Rodriguez; DA COSTA, Priscila Rezende; PEDRON, Cristiane Drebes. Proposição de estrutura alternativa para tese de doutorado a partir de estudos múltiplos. Revista Ibero Americana de Estratégia, v. 18, n. 2, p. 155-170, 2019.

Singh, R. K., Murty, H. R., Gupta, S. K., & Dikshit, A. K. (2009). An overview of sustainability assessment methodologies. *Ecological Indicators*, *9*(2), 189–212. https://doi.org/10.1016/j.ecolind.2008.05.011.

United Nations. Transforming Our World: The 2030 Agenda for Sustainable Development. 2015. Available online: https://sdgs.un.org (accessed on 15 November 2022).

2 TRENDS IN SUSTAINABILITY ASSESSMENT SUPPORTED BY GEOGRAPHIC INFORMATION SYSTEMS: A BIBLIOMETRIC APPROACH

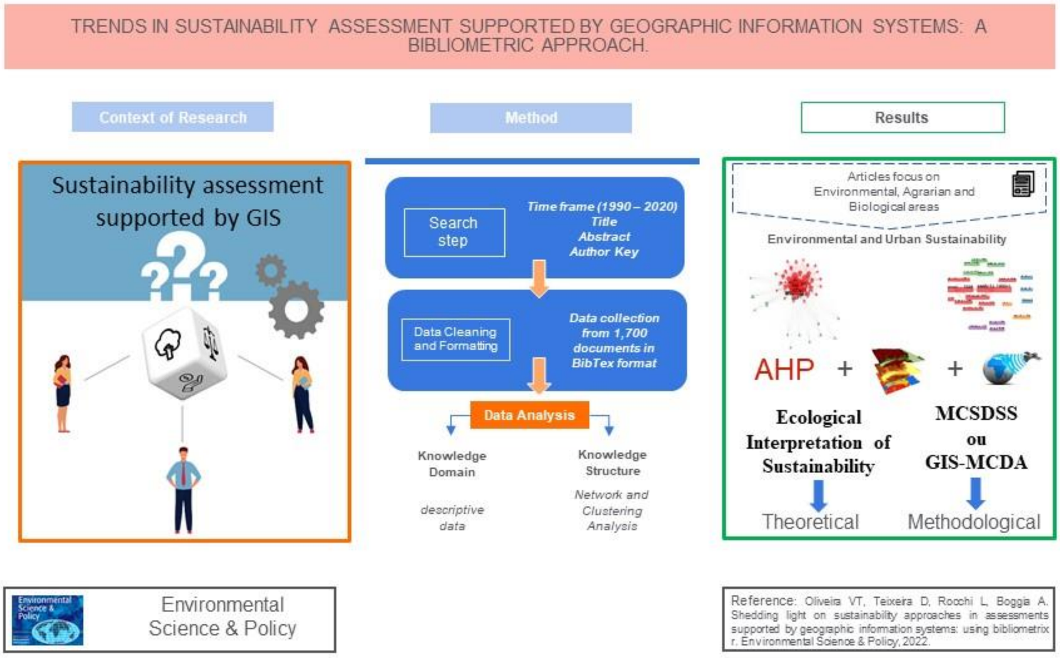


Figure 2.1 Visual abstract.

Abstract: The methodological process of Sustainability Assessment (SA) must be able to provide decision-makers with fundamental information that helps in understanding the human-nature interaction in different socio-environmental contexts. Among the tools that can support this evaluation process, Geographic Information Systems (GIS) has been pointed out as an emerging trend. However, the intrinsic complexity of the concept of sustainability can cause indecision about which approaches the GIS has effectively supported in the evaluation process. In this study, we apply bibliometric techniques for the characterization and structuring of knowledge (intellectual framework) to point out the different approaches to sustainability adopted in 1700 bibliographic records from the Scopus scientific database. The results indicate that the intellectual bases that guide the SA supported by the GIS are characterized by the ecological interpretation of sustainability. Furthermore, we point out that the methodological process is mainly characterized by the use of spatial analysis techniques, GIS tools integrated with remote sensing products, and Multicriteria Analysis Models, applied at local and regional scales.

Keywords: Sustainability, Geoprocessing, Remote sensing, Multicriteria Decision Analysis, Bibliometric analysis, *Bibliometrix-biblioshiny*.

2.1 Introduction

Sustainability assessment (SA) is a complex appraisal method, guided by a theoretical (goals of assessment, spatial scale, temporal scale) and a methodological framework (methods, tools, indicators) that vary depending on the approach to sustainability (Sala et al., 2015). It aims to fully support decision-making, through an integrated nature–society evaluation, at a local to global scale in short and long-term horizons (Devuyst, 2001; Ness et al., 2007).

The sources of SA complexity are several. Because of its ancient origins and the long theoretical evolutionary process, various definitions of sustainability coexist, as well as the presence of multiple indicators framework to define it (Estoque, 2020; Patterson et al., 2017). Such different possible interpretations of the concept of sustainability directly influence the evaluative process of nature-society systems, in particular considering the boundaries of such a valuation (Estoque, 2020).

Another aspect that has made sustainability assessment increasingly challenging is the scale issue. Sustainability assessment applications today must address global as well as local and regional issues, applying quantitative and qualitative indicators at different spatial scales (Gibson, 2016). Moreover, depending on the interpretation, it is relevant to consider that the interaction between environmental and social resources occurs in a geographical context, that is, they are embedded in dynamic spatial and temporal ecosystems, which can vary from global to local data, as well as from long to short term (Graymore et al., 2009). Therefore, the assessment methodology must be appropriate to use spatialized variables and, most importantly, provide results that support decision-makers in understanding the spatial dimension, not only of existing problems but also of the solutions to be proposed (Manning, 1990). Indeed, including the spatial dimension also in the solutions has proven to support decision-makers in more effective and efficient terms (Eide and Stølen, 2012). This requirement has presented the scientific community with major challenges regarding the need for efficient yet reliable instruments, which has led to the growth in the number of instruments used (Ness et al., 2007).

Methodologically, the main tool capable that can meet these conditions is the Geographic Information System (GIS): as illustrate in Fu (2020) geodata and geographical models for sustainability can be the basis of the Sustainability Science, as a transdisciplinary approach. This depends on the possibility of the contributions such tools can make to understanding the processes of natural and social systems and their mutual connection, as well as to clarifying the relationships between the structure, functional characteristics and interactions of human-environmental systems at multiple scales (Fu, 2020). GIS can support the storage and processing of spatialized data, as well as provide efficient visualization of results in a geographic context (Manning, 1990; Amelin, 1995). Perhaps, this is why a large number of works, in different knowledge areas, have applied or suggested the use of GIS techniques and tools to support the SA process (Manning, 1990; Yadav et al., 2010; Wightman et al., 2015; Mamat et al., 2018; Delgado, 2018; Vitor et al., 2020; Fu, 2020). However, although scientific papers have been recommending the use of GIS to support SA since the 1990s, it is only recently that some authors have found it to be a methodological trend in studies dealing with the measurement of SD (Olawumi and Chan, 2018).

Meanwhile, this finding permeates two important discussions. On the one hand, there is a great deal of effort in the debate on the definition and applicability of the concept of sustainability, which involves identifying the different types of sustainability that are to be assessed and the different methodological approaches that are to be followed for this purpose. On the other hand, there is a relentless search for new technologies that facilitate the production of sustainability assessments capable of generating results that support more assertive decision making (Ness et al., 2007). Therefore, despite the indication of a trend in the use of GIS, its application will depend on the interpretation of sustainability advocated by the assessors, which implies knowledge of the theoretical basis and the methodological guidelines to be considered.

Therefore, this study aims to identify what approaches to sustainability are used by GIS-supported SA work. To achieve these goals, we use bibliometric analysis techniques and tools, which also allow us to provide researchers with a broader understanding of the status quo of this domain.

2.2 Material and methods

Based on previous works, our research examines bibliometric performance indicators based on obtaining publications, collecting systematic data, and using bibliometric techniques, which include: the characterization of study areas, journals, authors, published documents, and the geographic context of the research, in addition to the co-citation and clustering analyses that allow mapping the intellectual structure of this research field (Rey-martí et al., 2015; Yataganbaba and Kurtba, 2016; Aria and Cuccurullo, 2017; Zyoud and Fuchs-Hanusch, 2017; Olawumi and Chan, 2018). Based on this bibliometric process, we conducted a qualitative analysis of the networks formed by the aforementioned authors and references, characterizing the approaches to sustainability adopted in selected scientific publications. This characterization was supported by Patterson et al. (2017) e Alfredo et al. (2018) who delimited different types of interpretation and meaning of sustainability.

Thus, based on an adaptation of (Ertz and Leblanc-Proulx, 2018) and (Secinaro et al., 2020), we consider a four-phase methodological process, which is illustrated in Figure 2.2.

Phase 1 begins with the definition of a scientific database to consult. Scopus was chosen as the database for searching publications related to the proposed topic because it is considered the largest scientific literature review database in the world (Campos-medina, 2021) and indexes more abstracts and citations from peer-reviewed literature than other scientific research databases (Aghaei Chadegani et al., 2013).

Afterward, we chose the primary keywords to perform an initial search, then the terms *geographic information system* and *sustainable development* were consulted to identify derivations that could be considered in a new search. This time, among a number of derivations, we decided to consider the documents that contained the terms: *geographic information system, geographical information system*, *gis, sustainability indicator, sustainable development*, and *sustainability assessment*. The use of these terms resulted in a set of papers that was as broad as possible and met the objectives of this work.

Only the documents classified as *articles* and *reviews* were considered in the research. This is because journal articles are considered more reputable sources, as well as having undergone a peer-review process (Olawumi et al., 2017). Furthermore, we performed the search considering finding the searched terms indexed in fields such as title, abstract, and keywords of the authors specifically (Tibaná-herrera et al., 2018), analyzing all years of publication available in the *Scopus* database, finding a total period of 31 years, i.e., from 1990 to 2020.

Phase 2 comprises data collection and cleaning. This phase enables the definition of a robust indexed corpus of research and thus the drawing of the intellectual scene in the field of GIS-supported research through a set of quantitative and qualitative bibliometric performance indicators.

However, the use of such terms in the database searches generated the return of some articles that covered other topics unrelated to the theme proposed in this research. Thus, we “cleaned” the performed search, using keywords related to the term GIS found after a thorough exploration of the articles assigned in each Subject Area. Some examples excluded from the search are: *Gigantea, Green Index, Geographical Indications,* and *Green Infrastructure.*

This time, we obtained the following search query in the Scopus database, obtaining a total of 1700 articles:

((TITLE ("geographic information syste*" OR "gis") OR ABS ("geographic* information syste*" OR " gis") OR AUTHKEY ("geographic* information syste*" OR "gis")), AND (TITLE ("sustainable development" OR "sustainability assessment" OR "sustainability indicator*") OR ABS ("sustainable development" OR "sustainability assessment" " OR "sustainability indicator*") OR AUTHKEY ("sustainable development" OR "sustainability assessment" OR "sustainability indicator*")) AND NOT (TITLE ("life cycle" OR "grassroot* innovation*" OR "Glycemic index" OR "Green indicator*" OR "Green infrastructure" OR "green information syste*" OR "geographic* indication*" OR "gigantea" OR "gi-cheol" OR "green index" OR "grazing incidence" OR "green innovation* strategy " OR "green investment scheme") OR ABS ("life cycle" OR "grassroot* innovation*" OR "Glycemic index" OR "Green indicator*" OR "Green infrastructure" OR "green information syste*" OR "geographic* indication*" OR "gigantea" OR "gi-cheol" OR "green index" OR "grazing incidence" OR "green innovation* strategy" OR "green investment scheme") OR AUTHKEY ("life cycle" OR "grassroot* innovation*" OR "Glycemic index" OR "Green indicator*" OR "Green infrastructure" OR "green information syste*" OR "geographic* indication*" OR "gigantea " OR "gi-cheol" OR "green index" OR "grazing incidence" OR "green innovation* strategy" OR "green investment scheme"))) AND DOCTYPE (ar OR re) AND PUBYEAR < 2021.*

For data collection, a *BibTex* (.bib) file was extracted with all the necessary data for the bibliometric analysis.

Phase 3 comprises a data analysis, which in turn was divided into two parts:

Part 1 - characterization of the knowledge domain, where we seek to understand how the research is distributed by study areas, in addition to identifying the main journals and authors who have published on the topic over the time frame (1990 to 2020).

Part 2- identification of the knowledge structure, where networks of co-citation and clustering of authors and references are generated (intellectual structuring).

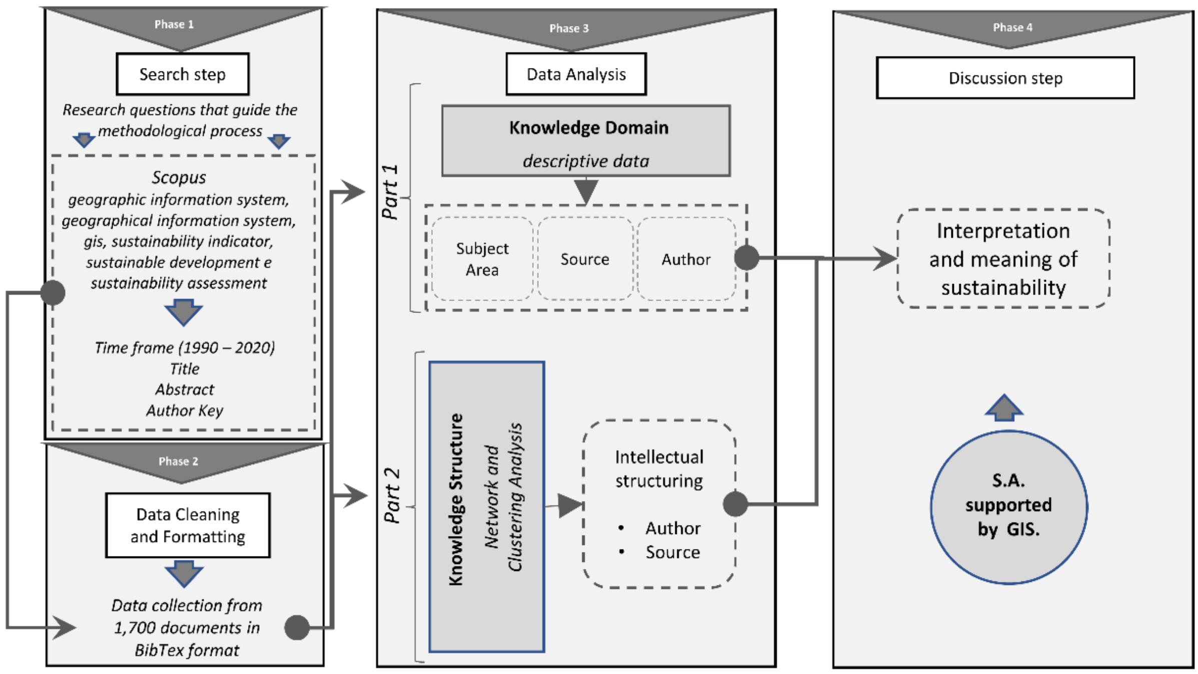


Figure 2.2 Infographic of the research steps.

Finally, phase 4 involves the interpretive stage that was identified, from the information obtained, how sustainability is conceptually and methodologically contextualized in studies involving SA supported by GIS. This characterization will be done qualitatively and will be supported by two studies that bring notes of different ways of interpreting and understanding sustainability.

First, Alfredo et al. (2018), defined different meanings of sustainability from an analysis of various scientific publications. This classification was determined by analyzing how the term *"sustainability"* was used and not by its conceptualization, resulting in four classes of usage, namely: as a set of criteria; as a vision or goal; as an object; as a study approach.

Second, Patterson et al. (2017) point out four different interpretations of sustainability to indicate the theoretical complexity of SA, namely: ecological interpretation; economic interpretation; thermodynamic and ecological-economic interpretation; interpretation through the approach of public policies, and the theory of planning for sustainability.

For the sake of clarity, Figure 2.3 lists the different meanings and interpretations of sustainability, as well as its theoretical characteristics and examples of use of the term found in the publications evaluated by (Alfredo et al., 2018).

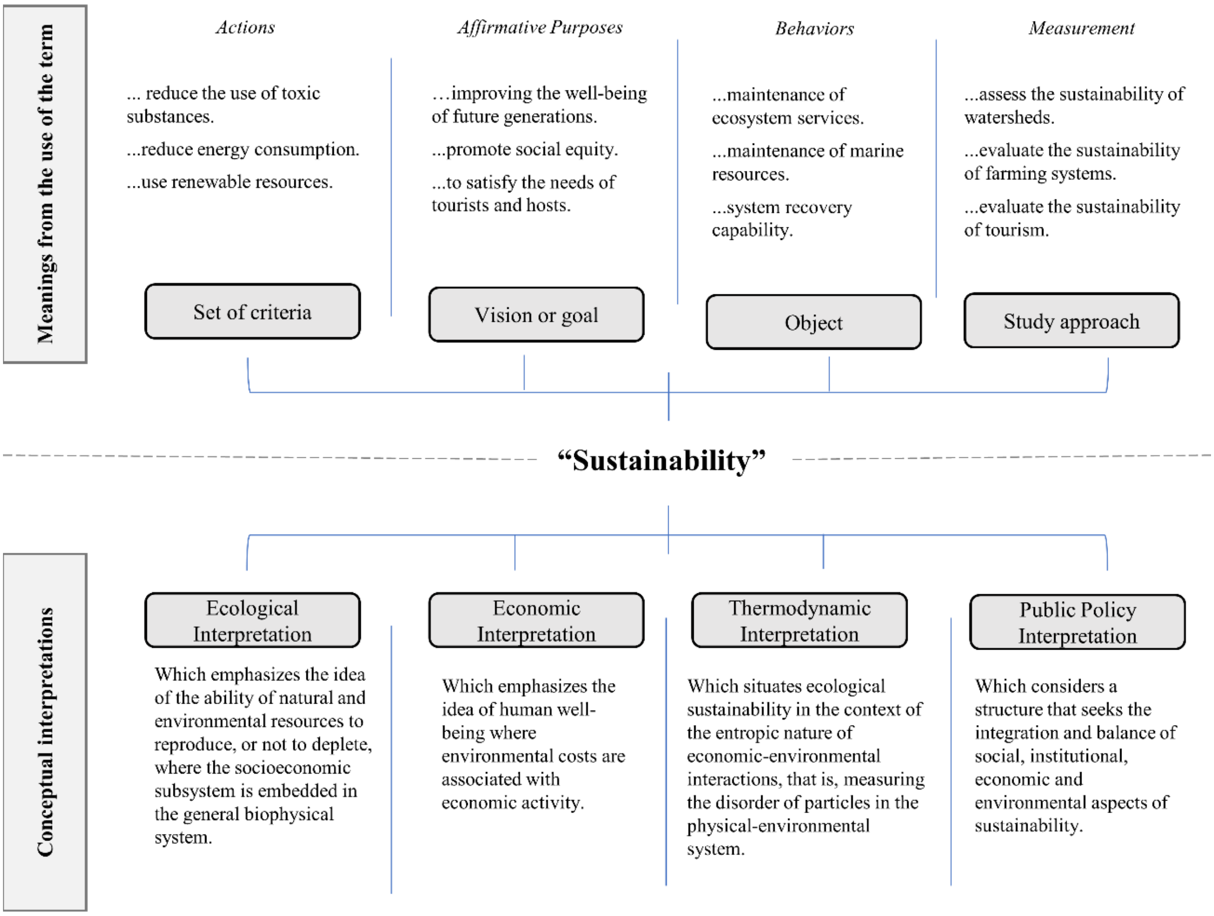


Figure 2.3 Sustainability Context. Adapted from Alfredo et al. (2018) and Patterson et al. (2017).

The use of the *bibliometrix R package* tool with the *biblioshiny* application runs through all the steps mentioned, from the web interface. The *bibliometrix R* package (http://www.bibliometrix.org, accessed on 01 June 2020) is equipped with a set of scientometric tools, written in the R language. This tool was preferred because it provides efficient statistical algorithms and integrated visualization tools that enable a more comprehensive interpretation of the analyzed research field (Aria and Cuccurullo, 2017).

Thus, from the mapping of the knowledge domain and intellectual structure, a qualitative analysis was carried out to identify the approaches to sustainability in the SA research field the supported by the GIS.

2.3 Results

The results are divided into two groups. The first focuses on the characterization of the knowledge domain, which is done from the identification of the main areas of study where the documents are concentrated, the main journals that have published on the topic, and the most represented authors, as well as the geographical context involving all the selected publications.

The second one focuses on the knowledge structure. This group comprises the contextualization of knowledge from the analysis of an intellectual structure, through the generation of networks and clusters of authors and the cited references.

2.3.1 Characterization of the knowledge domain

Following the search strategy, we selected article (1,642; 97 percent) and review (58; 3 percent) type papers, for a total of 1700 documents. Based on this result, and considering a time series of thirty-one years, we calculated an annual average of about 55 publications. However, when analyzing the annual publications, we see a significant increase in the number of papers published from the year 2010 onwards (Figure 2.4). In other words, in the decade from 2010 to 2020, the growing interest in the study of SA supported by the GIS has led the scientific community to publish 1,333 documents, representing 78% of the entire literature surveyed.

Furthermore, we found that these 1700 documents, counted individually, were cited 20,988 times by year 2020, which corresponds to an average of 12 citations per document. It is important to note that in this case global citations were considered, that is, the sum of all citations received by each selected article over the entire defined time frame (1990-2020) through the official Scopus database site page. This means that self-citations were also considered, which corresponds to about 13% of the total (2,778 papers). According to Van Noorden and Singh Chawla (2019) the self-citation rate can vary between 12% and 15.5% on the ground of different researches: nationality, stage of career and even the gender can affect the rate. However, self-citations should not be seen as a good or bad thing regardless because they are a more complex issue to deal with, with unclear consequences in terms of scientific output (Van Noorden and Sigh Chawla, 2019). We believe it is also important to point out that the 17 papers with the highest number of citations despite representing only 1% of all papers, collect as much as 15% of all citations. Moreover, when we examined the cumulative values, we found that between 2018 and 2020 alone, that is, in the last three years, these same documents were cited 9,995 times, which represents 47 percent of all citations received in the 31 years considered. This confirms the strong expansion of the scientific community's interest in the topic in the most recent years.

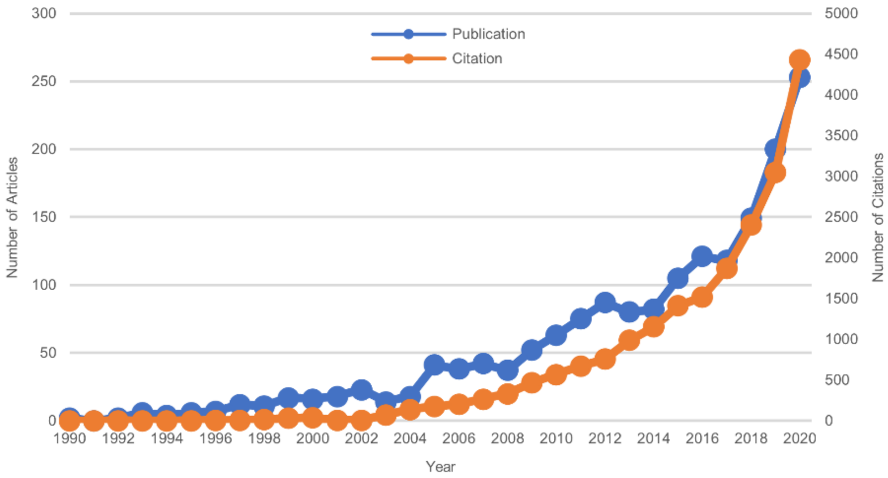


Figure 2.4 Distribution of the indexed research corpus and citations from 1990 to 2020.

2.3.1.1 Areas of study

Analyzing the distribution of scientific research in the field of GIS-supported SA by study areas, we verified that the articles were distributed into 24 categories. However, we noted that the articles mainly focus on the area of environmental sciences, followed by social sciences, earth and planetary sciences, and agricultural and biological sciences. Together, these four areas account for about 86% of the publications considered.

2.3.1.2 Journals

It is important to identify journals that publish research on the topic in which you are interested (Tsay, 2008). Considering the concentration of publications by journals, we identified that ten journals published 337 articles, which represents approximately a quarter (19.8%) of all publications, listed in Table 2.1. The journals *Sustainability Switzerland* and *Shengtai Xuebao Acta Ecologica Sinica* are the sources with the widest scope on the topic and were used mainly by Chinese researchers. However, we emphasize that the number of papers identified by each journal refers to the sum of all types of editions, i.e., publications in regular issues, special issues, collections, and sections, which might influence the result obtained.

Table 2.1 Top journals.

Ranking	**Source**	**No. of Docs (%)**	***h-index***	**Citations by No. of Docs**	**CiteScore**

1º	Sustainability Switzerland	95 (5.5)	16	667	3.9
2º	Shengtai Xuebao Acta Ecologica Sinica	57 (3.3)	12	331	1.4
3º	Nongye Gongcheng Xuebao Transactions Of The Chinese Society Of Agricultural Engineering	39 (2.3)	10	294	2.7
4º	Environmental Earth Sciences	28 (1.6)	13	549	4.5
5º	Environmental Monitoring And Assessment	23 (1.3)	10	336	3.6
5º	Land Use Policy	22 (1.2)	13	362	7.5
7º	Wit Transactions On Ecology And The Environment	20 (1.1)	3	18	0.6
8º	Chinese Geographical Science	18 (1.0)	8	169	4.1
9º	Dili Xuebao Acta Geographica Sinica	18 (1.0)	8	245	3.7
10º	International Journal Of Sustainable Development And World Ecology	17 (1.0)	8	177	5.5

Along with the number of global citations, the h-index value, which quantifies scientific production and captures the visibility of the work published by the authors (Rey-martí et al., 2015), was also considered. In this sense, among the journals that published the most, we identified *Sustainability Switzerland* as the one with the highest number of citations (667), followed by *Environmental Earth Sciences* (549), *Land Use Policy* (362), *Environmental Monitoring and Assessment* (336) and *Shengtai Xuebao Acta Ecologica Sinica* (331). Even considering the h-index, the journals *Sustainability Switzerland*, which reaches a H- index of 16, and *Land Use Policy* (H- index 12) stand out.

The Cite Score value is a metric defined by Scopus based on the number of citations and documents published in the last four years. In this regard, the journals *Land Use Policy* (7.5), *International Journal of Sustainable Development and World Ecology* (5.5), and *Environmental Earth Sciences* (4.5) emerge.

2.3.1.3 Authors

The number of citations received by an article, and the studies cited in a paper are two of the widely used bibliometric indicators to determine the relevance of an article (Duque Oliva et al., 2006). However, the number of citations received by an article may be due to the popularity of the author or the article's research field, and not to the relevance of the article itself (Rey-martí et al., 2015). Therefore, despite we identified a total of 4,847 different authors in this study, we will emphasize those who obtained the highest number of citations in the SA-supported GIS research (Table 2.2).

Table 2.2 Main authors.

Ranking	Author	Nº of docs.	%	Affiliation*	Citation	h-index
1º	Asadi, S.S.	14	0.6	Vignans Foundation for Science Technology and Research University Academics and Professor Department of Civil Engineering, Guntur, India	53	4
2º	Li, X.	10	0.5	East China Normal University, School of Geographic Sciences, Shanghai, China	1.141	10
3º	Pradhan, B.	8	0.6	University of Technology Sydney, Sydney, Australia	135	7
4º	Wang, K.	7	0.5	Zhejiang University, Hangzhou, China	82	6
5º	Adinarayana, J.	6	0.4	Indian Institute of Technology, Bombay, Mumbai, India	115	3
5º	Xie, H.	6	0.4	Jiangxi University of Finance and EcoNomics, Nanchang, China	130	5
5º	Yeh, A.G.O.	6	0.4	The University of Hong Kong, Department of Urban Planning and Design, Pokfulam, Hong Kong	849	6

**Affiliation gained by Scopus, based on the latest publications.*

2.3.2 Knowledge Structure

The *bibliometrix-biblioshiny* was used as a tool to understand the distribution and structure of GIS-supported SA research over the years. In this case, clusters are identified, meaning that each cluster corresponds to an underlying theme, topic, or line of research (Chen et al., 2010). In this work, we mapped the *clusters* of authors and references, which allowed us to analyze of the intellectual structure.

2.3.2.1 Intellectual Structure - author co-citation

A co-citation network was generated. It is important to note that the co-citation, in this case, does not consider the authors who developed the works that are part of this research corpus, but those who were cited by them. Thus, the *bibliometrix-biblioshiny* tool was able to identify which of all the authors were the most cited and, from the lines connecting them, perceive those with the highest frequency of co-citation. This indicates that when authors who are part of the network are read in connection, they should have greater cognitive effects on the reader (White, 2015).

Figure 2.5 identifies how authors are distributed in a network using the *Louvain* clustering algorithm. This method is quite accurate and works very well in large co-citation networks, in addition, it uses the notion of modularity, which measures the significance of dividing the network into communities (Zupic and Čater, 2015). Two elements can be identified on the map that help characterize the intellectual structure of this research field, namely the size of the nodes, which indicates the level of co-citation a given author has received from other researchers, and the distance between authors and subgroups, which indicates the degree of intellectual affinity between them.

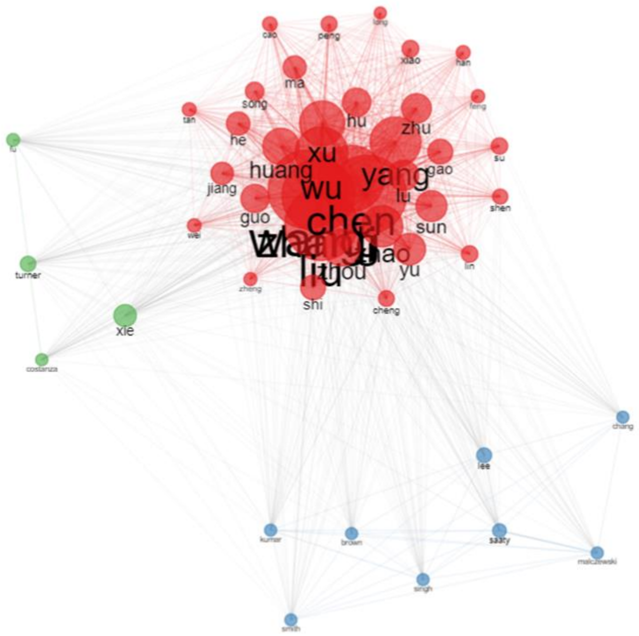


Figure 2.5 Authors' co-citation network.

The results in Figure 2.5 show three subgroups of cited authors that help represent the intellectual structure of publications in GIS-supported SA research. The largest network (red) consists mainly of authors *Wang*, *Li X.*, *Zhang*, *Liu and Chen*. These authors compose a cluster of 124 occurrences and have the highest values of citation frequency. The second largest network (blue) is distinguished by the high frequency with which authors *Saaty TL* and *Malczewski J* are cited along with other authors. The distance of the blue subgroup from both the red and green subgroups indicates less frequent co-citation among its authors and consequently less intellectual affinity. The third subgroup (green), with emphasis on author *Constance R.*, has a greater intensity of ties with the red subgroup.

2.3.2.2 Intellectual Structure – co-citation of references

Figure 2.6 reports a map representing the results obtained after identifying the five clusters of reference co-citation by applying the clustering algorithm *Louvain*. The clusters were characterized in descending order of size.

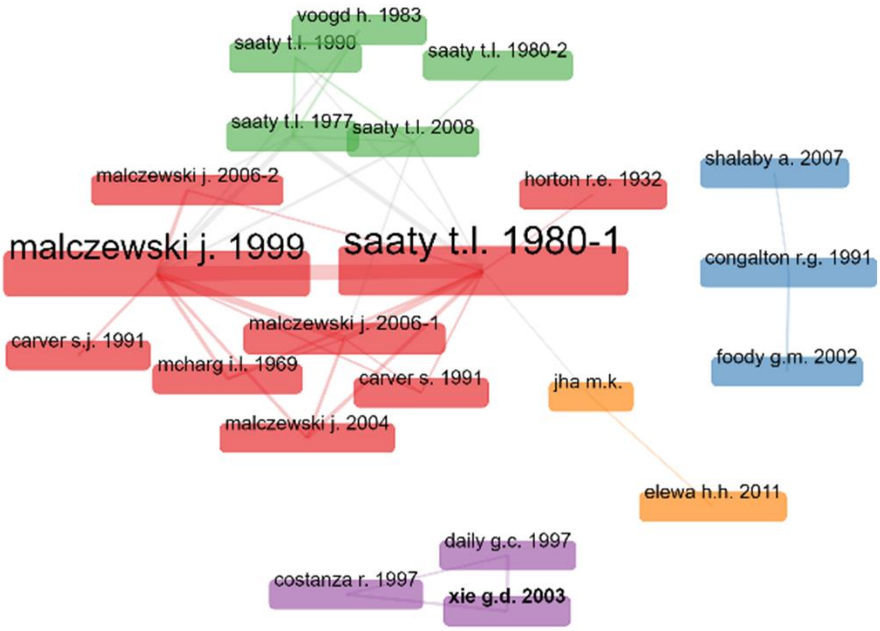


Figure 2.6 Referral co-citation network.

The red clusters (9 references) and the green cluster (5 references) have similar theoretical characteristics, despite having been classified separately. These are the papers that form the intellectual basis of works using methodologies that apply Multicriteria Spatial Decision Support Systems (MCSDSS or GIS-MCDA), i.e., they are multicriteria analysis researches in which the spatial variable must be included. *Malczewski J*'s publications are strongly cited with the book published by *Saaty TL*, (*The analytic hierarchy process: Planning, priority setting, resource allocation - 1980*) where he initially proposed the AHP method.

The blue cluster includes works that forms an intellectual base focused on the methodological process of mapping and categorizing land use and land cover based on the use of digital images. The purple cluster is mainly represented by the references Daily (1997) and Costanza et al. (1997). These two publications provide the fundamental intellectual basis for the ecosystem goods and services valuation work of Costanza et al. (1997). The orange cluster is the smallest among those identified. This subgroup forms a specific intellectual basis for works addressing groundwater planning and management, having in their methodological processes the use of GIS tools and remote sensing techniques.

2.4 Discussion

When we analyze the first group of results (knowledge domain characterization), it becomes clear how research on SA supported by GIS has attracted the attention of researchers in recent years. The growth in the number of papers published in recent years, as well as in the number of citations received, strongly indicates this. The areas of study, as well as the journals that publish the most on the topic, indicate that the research questions driving the work are related to ecological, environmental, and biological issues, aimed at understanding land use and focused on supporting decision-making.

By analyzing the authors in detail, moreover, we can understand, specifically, the areas of activity as well as the processes and methodological tools most commonly applied in these studies. We begin by pointing out author *Asadi SS* whose work focuses on the engineering area and who develops environmental analyses with frequent use of GIS tools and remote sensing products, focusing on the development of web-based decision support systems (Sarma et al., 2016). Authors *Li X* and *Yeh AGO* are similarly distinguished by the high number of citations they have received in papers that apply remote sensing techniques and focus primarily on urban sustainability from land use planning, combining land use maps and economic data (Li and Yeh, 2000). Author *Pradhan B.* appears in this research with studies focused on generating maps of environmental risk and vulnerability, mainly erosion and landslides, using computational techniques, with the application of multicriteria decision analysis systems and GIS tools (Abdullah et al., 2015). *Wang K.* stands out here for the analysis of the growth of urbanization and the impact generated on the quantity and quality of arable land, using GIS and Remote sensing (RS) tools (Deng et al., 2011). The author *Adinarayana J* contributes with studies focused on the river basin prioritization analysis through the use of multi-criteria decision analysis and the *Analytic Hierarchy Approach-AHP* method in particular (Aher et al., 2013), while *Xie H* focuses his research on the application of GIS tools for economic ecological assessments mainly in China (Xie et al., 2014; Xie et al., 2020).

For the discussion of the second group of results (intellectual structure) it is important to emphasize that the co-citation network analyses imply that the greater the number of citations shared between two publications, the greater the likelihood that these articles (or authors) share and corroborate a specialized language and a specific worldview (Boyack and Klavans, 2010). From this premise, we can deduce that nodes belonging to the same cluster in a co-citation network treat the topic of interest from a similar perspective (Hausberg et al., 2019). Therefore, when analyzing the authors' co-citation network, we realize that they are divided, but interconnected, in three different sets.

The first and largest network (red) has authors present in the references of work that focuses on mapping the evolution of land use and land occupancy and on simulating, through cellular automata models, the future situation of urban areas, water bodies, forest areas, croplands, etc. The combination of GIS tools and remote sensing products is common in these works, especially the use of multi-temporal satellite imagery. The second network (blue) is characterized by the high frequency of co-citation of two authors mainly. On the one hand, *Saaty TL* who is responsible for developing the AHP multicriteria decision analysis method, which helps make complex decisions based on expert evaluation of the performance of alternatives. (Cinelli et al., 2014). On the other hand, *Malczewski J* built-up the methodological basis of spatial integration decision problems in MCDA. The application of GIS techniques and MCDA models and tools is prioritized here and allows for a more effective decision making (Bottero et al., 2013).

Among the articles that materialize this network of co-citation of authors, the most visible is Huang et al. (2011) which brings a review of more than 300 articles published between 2000 and 2009 that reported on the use of Multicriteria Decision Analysis Models (MCDA) in the environmental field and already suggested a growing use of multi-criteria methodologies. Among the more recent articles, many of them have used MCDA for groundwater-focus assessments (Ahmed II and Mansor, 2018; Ahmed and Sajjad, 2018; Singh et al., 2018), as well as for the assessment of renewable energy areas (Alami Merrouni et al., 2018) and sustainable urban land use development (Dong et al., 2018).

The third network (green) highlights the large amount of co-citation between *Costanza R*. and other authors. Considering the articles that stand out the most in terms of the number of citations in this network, we note work with a strong focus on the valuation of ecosystem goods and services, as in the case of Grêt-Regamey et al. (2008) who spatially assess upland areas from the use of geographic data and GIS tools and Kienast et al. (2009) who use binary links in the assessment of land use functions in which the supporting or neutral role of the landscape for certain functions can be tested.

Regarding the reference co-citation network, we identified five different clusters and used an approach based on the publications with the highest number of citations to describe them. The red cluster consists of papers that form a fundamental theoretical and methodological basis for integrated MCDA-GIS applications, in which the principles and philosophy of multicriteria decision making must be adhered to (Malczewski, 1999; Malczewski, 2004; Malczewski, 2006). The second cluster (green) deals with fundamental theories and applications for the use of the AHP method (Saaty, 2008) especially in economic, social, and engineering fields (Saaty and Vargas, 2012). The blue cluster focuses on cartographic processes for representing land use. Efforts are highlighted to evaluate the precision and accuracy that are achieved using remote sensing-derived imagery (Congalton, 1991) through the use of error matrices (Foody, 2002) are highlighted. The purple cluster represents a set of references with important theoretical underpinnings for work facing the valuation of ecosystem services. Indeed, although the concept of ecosystem services was initially addressed in Westman (1977) it was Nature's Services: Societal Dependence on Natural Ecosystems (1997) and the article "The value of the world's ecosystem services and natural capital", published in *Nature* in 1997, that filled the role of conceptual popularization of this field of research (Estoque, 2020). Among the works that cite them, the practice of using spatial data with the high spatial resolution is common. The orange cluster is composed of references that are frequently cited in groundwater studies and that use geoprocessing and remote sensing techniques. To exemplify we cite Peiffer (2007) that presents an extensive review of the concepts of GIS and remote sensing; from a survey of the literature, the authors were able to classify six main areas in which these geospatial tools and products are applied in the context of hydrogeology, namely, the exploration and evaluation of groundwater resources, the selection of artificial recharge sites, underground flow and pollution modeling, groundwater pollution risk assessment, natural recharge distribution estimation, and hydrogeological data analysis and process monitoring. In Elewa and Qaddah (2011) the authors integrate hydrological modeling and geostatistical calculations with GIS and remote sensing to rank the potential of different groundwater storage locations.

2.4.1 Further remark about the intellectual structure and knowledge domain

The interpretations and meanings of sustainability classified by Alfredo et al. (2018) and Patterson et al. (2017) guided this stage of discussion of the results.

Thus, if we analyze the results obtained in the knowledge domain characterization phase, we realize that the articles are strongly concentrated on Environmental, Agricultural, and Biological Sciences and that the main journals prioritize themes such as environmental and urban sustainability. However, the most cited publications are studies that relate sustainability to the selection and preservation of environmentally sensitive areas and the relationship between the abandonment of rural areas due to regional socioeconomic characteristics. Therefore, it is clear that these are works that, while using multidimensional variables, focus on analyzing the direct reflection of human activities in the ecological subsystem.

Among the most prolific authors, there is a concentration of research that used GIS tools and Remote Sensing techniques to map land use contextualized to environmental vulnerability assessment (Abdullahi et al., 2015). The strong predominance of ecological interpretation of the studies that make up the body of research is evident, as only biophysical variables are included in the evaluation process. Land use mapping is also present in research that monitors and predicts the progress of urban areas for planning purposes (Li and Yeh, 2000). This situation is repeated if we look at the most cited publications in major journals (Liu et al., 2019; Faichia et al., 2020)

If we consider the analysis performed by knowledge structure mapping, we can identify the intellectual foundations that support GIS-supported SA research. These bases are composed of networks of authors' co-citations and references (intellectual structure) and show three main categories of approaches to sustainability.

The first category identified is characterized by works that interpret sustainability from an ecological perspective and where the term is commonly used to determine a set of rules to be applied in certain systems. This is because the studies that make up this category focus primarily on mapping land use patterns or detecting changes in its coverage, providing scientific support for decision makers to conduct human actions in reducing negative impacts on the ecological system.

This intellectual structure consists of authors such as *Wang, Li X, Zhang, Liu X, Chen, and Yang,* among others, who provide theoretical support to direct and justify researches that assess the progress of human activities in natural areas (Aburas et al., 2016; Birkmann, 2007) with methodologies that include the use of GIS and RS products. The works are mainly focused on risk assessments and natural disasters, the progress of urban sprawl in arable areas, and the loss of natural areas for monoculture use (Ettazarini, 2006; Birkmann, 2007; Saidi et al., 2011; Gimpel et al., 2013; Arnous and Omar, 2018).

The second category also fits an ecological interpretation, but unlike the first, sustainability is here understood as a behavior of the studied system. Composed by authors such as *Constanza, Fisher B, Turner, Forman, Wu, Daily GC, and Vitousek PM,* among others, this intellectual base supports, theoretically and methodologically, publications that interpret sustainability from the dynamism between the landscape and human welfare services, where terms such as “balance”, “adaptation” and “resilience” are quite frequent.

Research on the valuation of ecosystem goods and services makes use of GIS techniques and tools to analyze landscape changes and dynamics. Some authors have focused their work on this field of knowledge, assessing the relationship of ecosystem services to sustainable environmental development. (Hu et al., 2013; Zhao et al., 2013; Shi et al., 2013).

The third category, in line with the previous ones, mostly presents an ecological interpretation of sustainability. However, there is a miscellany of meanings arising from the use of the term "sustainability," and here we highlight the two most frequent: as an approach to studies, in research that seeks to assess the sustainability of particular systems from multidimensionality and resulting in indices that seek to translate the performance of social, economic, and environmental variables (Graymore et al., 2009; Boggia et al., 2018) and as a set of social-ecological criteria, in research concerned with determining optimal locations for human intervention in a given subsystem, generally focused on planning (Romano et al., 2015). However, the main characteristic of this category is that the intellectual base formed by authors such as *Saaty, Malczewski, Jankowski, Eastman JR, and Chen Y*, and others, guides the SA research supported by GIS fundamentally by the methodological process, from the application of models of multi-criteria analysis.

It is worth highlighting the use of procedures that spatially integrate the variables to the multicriteria analysis models, through the application of GIS techniques, called the Multicriteria Spatial Decision Support System (MCSDSS). It is common among studies in this category the use *MCDA* models, such as the *AHP*, which are used to structure complex decisions using mathematical processes to help select decisions to be made based on an order of alternative preferences (Malczewski, 2006). Furthermore, the MCSDSS becomes important when it is necessary to consider spatial information in decision-making, for that, it unites GIS and MCDA, generating spatial information resulting from the preferences of decision-makers.

As an example, we highlight the use of geolocation to select areas for the installation of waste and renewable energy treatment plants. This is an object of study that has been widely explored by the works found in this research, especially when aimed at evaluating the potential of sites for hosting plants and photovoltaic, wind, and even biomass farms (Aydin et al., 2010; Aydin et al., 2013; Sultana and Kumar, 2012; Uyan 2013; Latinopoulos and Kechagia, 2015; Alami Merrouni et al., 2018). Still, others address the process of selecting optimal areas for installing landfills (Ferretti, 2011), waste incinerators (Ferretti and Pomarico, 2012), and ecological corridors (Ferretti and Pomarico, 2013).

2.5 Conclusions

The application of bibliometric techniques, analyzing 1700 articles published between

1990 and 2020 indexed in the *Scopus* database, enabled the characterization of theoretical and methodological approaches to sustainability, as well as to map the global trend in SA with the support of GIS, the main objectives of this work.

The characterization of the knowledge domain and structure carried out with the support of the *bibliometrix-biblioshiny* tool proved to be efficient and accurate in identifying the intellectual bases.

Based on these results, and with support from previous work, we identified that GIS-supported research in SA addresses sustainability primarily from an ecological perspective, where the focus is on environmental quality variables. Moreover, sustainability research is sometimes understood as a set of criteria formulated to guide actions to be taken, sometimes as the ability of a given system to maintain its characteristics despite human pressure. Additionally, the term “sustainability” is used more frequently in two ways: as a set of socio-ecological criteria that are intended to guide human actions that would make a given system sustainable; and as the ability of certain systems to maintain characteristics, or functions, over time, despite disturbances.

Regarding the methodological process involving GIS-supported SA, we have verified the predominance of geoprocessing techniques, in which GIS tools and SR products are mainly applied in mapping patterns and changes in rural or urban land use and occupancy, at local or urban scales. And, when integrated with MCDA techniques, focus on solving decision problems in which the spatial variable is indispensable.

We believe that the information generated here will be supportive of future research focusing on this field of research. The main contribution is the broadening of the knowledge about the SA- GIS supported which is shown to be a rising field of analysis.

2.6 Study limitations/Strengths

Scopus is considered the largest database that indexes a large number of literature abstracts and peer-reviewed citations than other scientific research databases (Aghaei Chadegani et al., 2013). However, the non-use of other databases, in addition to the omission of theses, dissertations, and conference papers, may have excluded research or authors that would contribute to the discussion of the topic.

On the other hand, this work analyzed a total of 1700 articles, providing valuable data for researchers and professionals who dedicate efforts to the GIS and Sustainability fields, bringing important information about the sources that stand out for consultation.

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3 GEOGRAPHIC INFORMATION SYSTEM APPLIED TO SUSTAINABILITY ASSESSMENTS: CONCEPTUAL STRUCTURE AND RESEARCH TRENDS

Abstract: The conceptual variations and divergences that permeate the debate on sustainability end up directly reflecting the choice of sustainability assessment (SA) processes, providing different methodological approaches. Among them, some researchers have pointed out challenges, but also opportunities to use geospatial data, techniques, and tools as resources to be explored in sustainability assessments. However, it was still unclear how geospatial tools have contributed in this context, as well as their future potential. Thus, through bibliometric mapping, this research answers these questions, through the identification of both the thematic fields of action of the geographic information system (GIS) in SA as well as the emerging research areas in this domain of knowledge. For this, we selected 1721 articles spanning 31 years (1990–2020). We observe that this is a subject of growing interest, as more than 50% of all publications were published after 2015. The main results indicated that, initially, the GIS supported sustainability assessments as a mapping tool associated mostly with environmental issues, however, the evolution of the analysis potential, through data modeling, gives rise to new application perspectives. This evolution takes place, in parallel, with the global discussion on sustainability, where multidimensionality starts to play a leading role, and sustainability indicators assume geographic positions.

Keywords: sustainability; sustainability assessment; sustainability indicators; geographic information system; bibliometric analysis; bibliometrix-biblioshiny

3.1 Introduction

The debate on sustainability is as broad as it is old, and the problem surrounding its conceptualization is one of its main challenges. The use of terms that translated this meaning was first introduced in the literature by German researchers in 1713, who were concerned with forestry activities, in particular that the forest was never harvested more than it was able to replenish [1]. However, this discussion expanded globally from 1972 onwards, when concerns related to environmental issues were addressed at the UN General Assembly meeting at the Stockholm Conference, gaining an international priority status [2]. Later, in 1987, the term sustainable development (SD) was popularized from the report “Our Common Future” (Brundtland Report) into the one adopted by current generations to satisfy their needs without making it impossible for future generations to do the same, decreeing an intergenerational character to this concept [3].

Although widely accepted, the definition of SD adopted by the United Nations has been the subject of discussions about what it actually represents, as it is presented as a broad, ambiguous, imprecise, and sometimes contradictory concept [4]. These examinations are justified because it is an ingrained concept of cultural values that can define different principles [5], depending on the different interpretations that are given [6], making the evaluation process even more complex.

Such complexity translates into a huge diversity of sustainability assessment (SA) mechanisms found in the literature and which differ in their objectives, methods, and tools [7]. However, even if they differ in spatial and temporal scales, the SA ends up aiming to guide decision-making that leads the object of study to the path of sustainability [8]. This definition of SA can be expanded if, in addition to integrating sustainability issues into decision-making, it also promotes the sustainability objectives themselves, that is, being able to influence decision-makers, and this also contributes to the contextual interpretation of sustainability [9].

Among the SA methodologies that enable this exchange of information between evaluators and decision-makers, the application of sustainability indicators (SI) is probably the most popular internationally [5]. However, despite being popular, there is still no methodological (or even conceptual) consensus on the use of SI, and this is due to the very complexity of assessing what really matters for monitoring society's progress towards sustainability [7].

Through a very constructive debate, Ramos [7] points out some possible future paths for SA with SI by identifying a set of challenges found in the literature. Among the challenges and opportunities raised, the author highlighted the use of geospatial technologies (for example, remote sensing) as new approaches to indicators, which can be an important solution to mitigate the limitations and availability of data, especially for certain scales of analysis. The use of satellite data, for example, is still relatively unexplored.

However, despite still being a challenge, the concern towards approaching sustainable development (SD) geospatially is not recent. Even in the 1990s, Manning [10] warned that the SD path involves understanding the relationship between biophysical and socioeconomic information and that this requires a better understanding of the spatial dimension of both the problems and the proposed solutions. In other words, decision-makers must be able to interrelate, even spatially, information from many different sectors. The author is categorical in stating that, in this sense, a vital tool to achieve these goals is the geographic information system (GIS).

Nevertheless, even after three decades, important studies continue to point to the GIS tool and techniques as trends in SD measurement [11]. This trend, to some extent, is perceived through preliminary research in scientific databases, and in studies from different areas of knowledge [12–20]. However, while there is a discussion about the different interpretations of sustainability, it is also necessary to consider that the geospatial approach in SA will also occur in different contexts.

In this way, we understand that the role of GIS in SA is a scientific gap still to be explored. Thus, we postulate that, for greater effectiveness of the GIS application, it is necessary to understand in a more holistic way the thematic fields in which these geospatial tools act in the evaluations that aim to measure sustainability. To reach this understanding, it is necessary to explore the historical paths of scientific research that approach this field of knowledge, to identify how research areas evolve over time, even showing future scientific ways to be considered.

This research tries to clarify these points by the means of a bibliometric review, organized as follows. After the introduction, where the gaps in and the main objective of the research are presented, an overview is presented in Section 2, where some highly visible works on the subject are discussed, bringing to light what is known, so far, of the proposed research field. In Section 3, the methods applied in the development of the research are outlined, followed by Section 4, where the results found are reported. In Section 5, the main results are highlighted together with the discussion on the historical evolution of the themes that contemplate the use of GIS in SA. In Section 6, the final conclusions are presented, highlighting the contributions to knowledge where new frontiers are opened for future research.

3.2 Background

Assessing sustainability is not an easy task. The complexity of the evaluation process occurs insofar as there are several ways to interpret the concept of sustainability itself. In the studies by Patterson et al. [6] some SA tools were methodologically detailed to identify their common characteristics, and to exemplify the complexity of this evaluation process, the authors list four different interpretations of sustainability on which the different methods can be supported, namely: ecological, economic, thermodynamic, and ecological–economic interpretations, as well as interpretation by public policy and planning theory. Therefore, we can infer that the use of geospatial data, techniques, and tools can also take place in different contexts depending on the sustainability approach on which the assessment is based.

The use of GIS in SA has been encouraged since the 1990s, mainly because it allows analyses that interrelate environmental and economic variables, providing a more holistic approach to the relationship between the natural and human environments [10]. Since then, several works have been developed in which the GIS supports assessments that aim to understand sustainability at different scales, whether macro (strategic) or micro (operational) [7].

However, when consulting different publications that stand out on the subject, and which have had great scientific visibility in the last 30 years, one can see a variety of approaches in which GIS can support SA processes. In general, there is a consensus that GIS is applied to works that involve the treatment of spatialized data and that it produces results in the form of mapping, and even tables or graphs.

Nevertheless, other scientific knowledge can be added to GIS to obtain even more accurate results. In studies by Forsyth [21], for example, some indigenous knowledge was incorporated into spatial analyzes to measure soil erosion to test the assumptions that land scarcity has increased cultivation on steeper slopes and that erosion is a problem for the degradation of the highlands. In this example, the debate on the concepts of sustainable knowledge and "hybridity" stands out; it uses local and indigenous knowledge, together with global scientific techniques, to achieve guidelines for sustainable development focused on environmental issues.

However, if on the one hand the GIS appears to support sustainability assessments based on the analysis of the damage caused by action, the opposite is also perceived. This is what Joerin et al. [22], who carried out mapping of land suitability for housing in a region of Switzerland, posited. This mapping incorporated a set of complex criteria that integrated the views of several stakeholders, and a GIS was used to assess the criteria requested in the definition and suitability of land for housing. Therefore, predictive mapping appears as an option to support assessments.

In addition, other sciences can enhance mapping capability when used in conjunction with GIS tools. This is the case of products derived from remote sensing (RS), such as images obtained via satellite. In the cases of Weng [23], Cheng and Masser [24], and Xiao et al. [25], remote sensing is integrated with geographic information systems to detect urban growth and assess its impact on urban sustainability, in which the detection of land use and cover change plays a key role. Therefore, evolution in the support of GIS to SA can be seen with the increase of new sciences of observation of the earth's surface, however, this is still restricted to the use of biophysical data for the mapping of land uses. MacKerron and Mourato [26] differ in that they build a model that relates life satisfaction with a focus on air quality, in particular, using data from 400 London residents and GIS software to calculate pollutant concentrations in the vicinity of their homes. Despite this, GIS tools still appear to be applied in sustainability assessments that are directly related to environmental issues.

From the following decade, other examples of highly visible publications can be explored that show some sustainability approaches in which the evaluations applied, in different ways, use GIS tools in the methodological process.

Burkhard et al. [27] aimed to present and apply a concept of mapping, through GIS, the supply and demand of ecosystem services, which could be applicable at different scales and that allowed the comparison of different ecosystems, in addition to developing a tool in which landscape managers can rely on sustainability assessments. Jiang et al. [28] present a GIS-based approach to assessing the availability and distribution of agricultural waste in China, considering several conservation issues: resources (total amount, spatial and temporal distribution), economics (transport costs), environment, and technology, in order to assess the potential for conversion into bioenergy. In these studies, an ecological approach to sustainability is evident, where GIS presents itself as a support mechanism for decision-makers.

However, GIS allows, in essence, the application of variables from different categories, as long as they can be spatialized: not restricted to environmental/ecological data, but also to economic or social ones. In this sense, Bathrellos et al. [29] proposed an urban planning and sustainable development approach for Trikala City Hall (Western Thessaly, Central Greece). For this, several parameters were used and correlated by the method of the analytical hierarchical process (AHP) and incorporated in a GIS to produce the corresponding maps of suitability.

Therefore, we cite above some examples that can help to understand what is known, so far, of the support in which GIS techniques and tools provide the evaluations in which the authors indicate that they deal with sustainability. In agreement with what Patterson et al. [6]

and Sala et al. [5] affirm, the previous examples expose the complexity of SA precisely because of the diversity of interpretations depending on the principles in which sustainability is presented. Among the cited studies, sustainability assessments were perceived from the perspective of land use and occupation and its urban and rural planning, by the selection and suitability of areas, by the relation of life satisfaction and air quality, and by the supply and demand of ecosystem services, for the bioenergetic potential of areas and for the quality and management of water resources. This scenario turns out to corroborate the idea that, despite the use of GIS being pointed out as a methodological trend in SA [11], there is still no clarity on the themes in which these geospatial techniques work. We might ask what the directions of its application in future works are, and if they are paths that can lead decision-makers to direct the studied areas towards sustainable development.

Thus, we understand that a broad analysis, which is capable of understanding several scientific publications on the subject, such as an analysis of scientific mapping through bibliometrics, can help to answer these questions. Bibliometric works can be understood as a set of methods that help in the analysis of academic literature in a quantitative manner, but also in understanding the changes that occur over time in the field of research being analyzed. One of the main methods for exploring a field of research is scientific mapping (or bibliometric mapping), which consists of revealing the conceptual, social, or intellectual structure of scientific research, in addition to its evolution and dynamic aspects over time [30].

However, we realize that there is still no work in this direction which is capable of revealing the main themes addressed by the field of research of SA supported by GIS, as well as the most recent problems faced. In addition, research from this perspective can assist in the study of thematic evolution and point out global trends in this field of research. Based on this, we propose a bibliometric analysis that is able to include all the research published on the topic, and that can identify future paths from a historical analysis.

3.3 Materials and Methods

We consider a methodological process that involves four steps, adapted from [31,32], for an analysis of scientific mapping, which is illustrated in Figure 3.1.

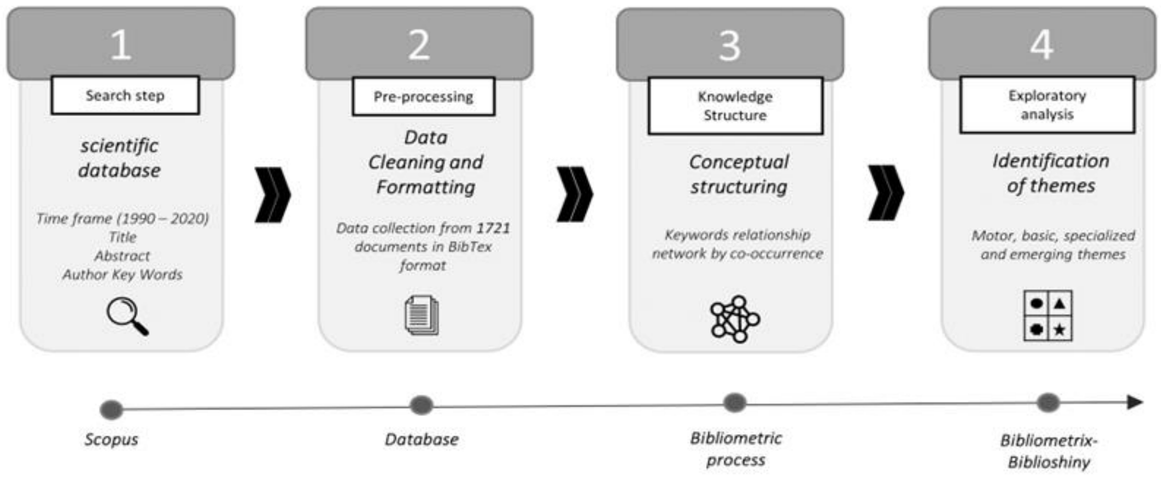

Figure 3.1 Methodological steps.

The first step consists of retrieving data from a scientific database. This step begins with the definition of the scientific database to be consulted. In this case, we chose to use the Scopus database to search for publications related to the proposed research field. Scopus was chosen because it is considered the largest scientific literature review database in the world [33], in addition to indexing a greater number of abstracts and citations of peer-reviewed literature compared to other databases [34]. The main weak point of Scopus is that it has some limitations for older records: however, because of the subject of the analysis, we can consider it not constraining [35].

A crucial moment of this stage is the choice of primary keywords, which will serve for an initial search. Later, derivations will be identified that could be considered in a new search. Here, we chose to search for the terms “geographic information system”, “geospatial knowledge infrastructures”, “spatial data infrastructure”, “geoverse”, “geoai”, “Service-Oriented Mapping”, and “sustainable development”. This time, in the midst of a series of derivations, we decided to consider the documents that contained the terms: “geographic information system”, “geographical information system”, “GIS”, “spatial data infrastructure”, “sustainability indicator”, “sustainable development”, and “sustainability assessment”. The use of these terms resulted in a broader set of articles that meets the objectives of this work.

In addition, only the types of documents classified as articles or reviews were considered in the search. This decision is justified because journal articles are considered more reputable sources, in addition to having undergone a peer review process [11]. Furthermore, we performed the search considering the terms indexed in fields such as title, abstract, and keywords of the authors specifically [36], analyzing all the years of publication available in the Scopus database, finding a total period of 31 years from 1990 to 2020.

The second stage is to carry out a pre-processing of the data to avoid the use of documents that are not part of the topic to be analyzed. Thus, we performed data cleaning, which resulted in a corpus robust indexed research.

It is notable, and widely known, that the term GIS is commonly used to indicate the use of techniques and tools that make up the geographic information system. Thus, in countless works it is common to find the use of the term GIS in the titles of scientific works, in their abstracts, and also in the keywords, without necessarily indicating its meaning, leaving it to the author's discretion to explain its meaning in the body of the text article. Therefore, the use of this term in the database searches generated the return of several documents that dealt with other subjects that were not related to the proposed research field. Thus, we cleaned the performed search, using keywords related to the GIS term found after a thorough exploration of the articles allocated in each Subject Area, and excluding them from the search process (examples: gigantea, green index, geographical indications and green infrastructure).

Therefore, we performed the following search query in the Scopus database, obtaining a total of 1721 articles:

((TITLE ("geographic* information syste*" OR "gis" OR "spatial data infrastructure") OR ABS ("geographic* information syste*" OR "gis" OR "spatial data infrastructure") OR AUTHKEY ("geographic* information syste*" OR "gis" OR "spatial data infrastructure")) AND (TITLE ("sustainable development" OR "sustainability assessment" OR "sustainability indicator*") OR ABS ("sustainable development" OR "sustainability assessment" OR "sustainability indicator*") OR AUTHKEY ("sustainable development" OR "sustainability assessment" OR "sustainability indicator*")) AND NOT (TITLE ("life cycle" OR "grassroot* innovation*" OR "Glycemic index" OR "Green indicator*" OR "Green infrastructure" OR "green information syste*" OR "geographic* indication*" OR "gigantea" OR "gicheol" OR "green index" OR "grazing incidence" OR "green innovation* strategy" OR "green investment scheme") OR ABS ("life cycle" OR "grassroot* innovation*" OR "Glycemic index" OR "Green indicator*" OR "Green infrastructure" OR "green information syste*" OR "geographic* indication*" OR "gigantea" OR "gicheol" OR "green index" OR "grazing incidence" OR "green innovation* strategy" OR "green investment scheme") OR AUTHKEY ("life cycle" OR "grassroot* innovation*" OR "Glycemic index" OR "Green indicator*" OR

“Green infrastructure” OR “green information syste*” OR “geographic* indication*” OR “gigantea” OR “gicheol” OR “green index” OR “grazing incidence” OR “green innovation* strategy” OR “green investment scheme”))) AND DOCTYPE (ar OR re) AND PUBYEAR < 2021.

For data collection, a BibTex file (.bib) was extracted with all the data necessary for the bibliometric analysis.

The third step corresponds to the selection of the unit of analysis and the relationship between them. In this study we propose the identification of the knowledge structure from the keywords present in the publications (conceptual structuring), thus building a relationship network through co-occurrence. This generated network can be understood as a graphic representation of co-occurrences from a set of terms that are extracted from the keyword lists of articles, titles, or abstracts. This graphic representation is also called a thematic map, formed from a Cartesian representation, where different clusters are defined and allocated into quadrants, facilitating the interpretation of research themes developed in a structure [37]. To carry out such analysis, we used the bibliometrix R package tool (http://www.bibliometrix.org, accessed on 9 June 2021) with the biblioshiny application, equipped with a set of scientometric tools, written in the R language. This tool was preferred to others because it provides efficient statistical algorithms and integrated visualization tools that allow a more comprehensive interpretation of the analyzed research field [38].

The fourth and final stage involves an exploratory and interpretive analysis that makes it possible to highlight the different topics included in this domain of knowledge, covering the entire period of publications and identifying the driving, basic, specialized, and emerging themes, as well as their trajectories over time.

3.4 Results

To illustrate the growing interest of the scientific community in works that develop SA and that, in their methodological process, use GIS techniques and tools, we historically detail the number of annual publications of all selected articles. Thus, a total of 1721 documents were collected based on a search strategy that includes articles (1642; 97%) and reviews (58; 3%). Based on these results and considering a time series that comprises thirty-one years, we have an annual average of approximately 55 publications. Furthermore, there has been a significant increase in documents published from 2008 onwards; in just over a decade, from 2008 to 2020, the growing interest in the study of SA supported by GIS led the scientific community to publish 1387 documents, representing more than 80% of all publications raised.

3.4.1 Knowledge Structure

The knowledge structure comprises the contextualization of science from the analysis of the conceptual structure, which was explored through thematic mapping using the keywords of the authors who composed the publications.

In this case, clusters are identified, which means that each cluster corresponds to an underlying theme, topic, or line of research [39]. In this work, we mapped the keyword clusters, making it possible to analyze the conceptual structure.

Conceptual Structure—Keyword Clusters

From the file generated after searching the Scopus database, we grouped similar keywords in order to avoid overlapping equivalent terms (e.g., GIS, geographic information system, geographical information system). After this process, we identified a total of 4673 different keywords for a total period of 31 years. Figure 3.2 shows the 20 keywords with the highest number of occurrences.

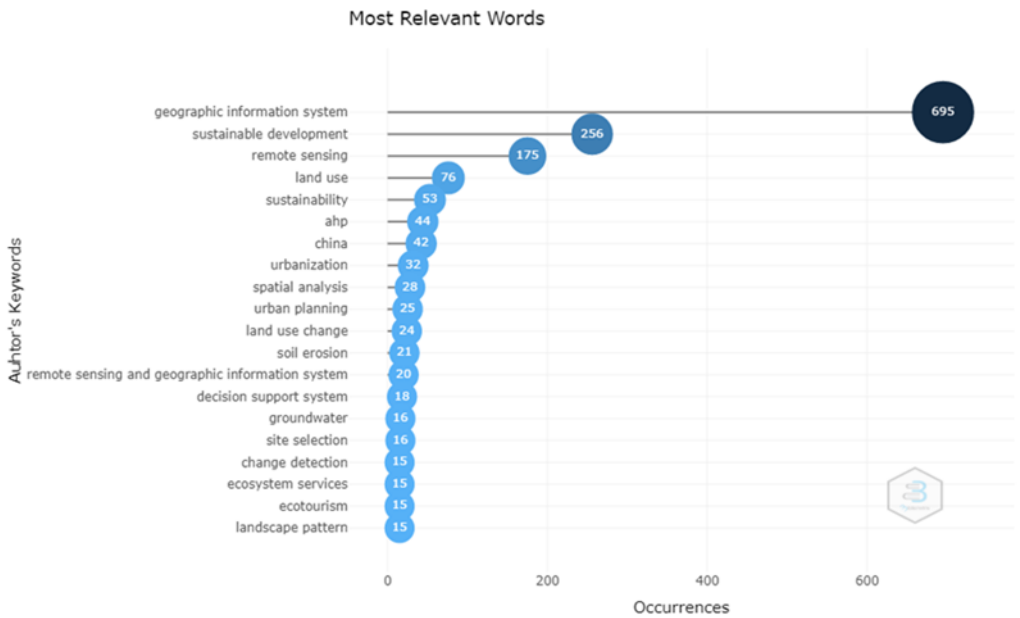

Figure 3.2 Most frequent keywords.

Therefore, it is clear that the keywords “Geographic Information System”, “Sustainable Development”, and “Remote Sensing” not only occurred in high frequencies but also occurred throughout the analyzed period (1990 to 2020). However, terms such as “Land Use”, “China”, and “Urbanization” are terms that have appeared in high frequencies in the last ten years. The words ecotourism, urban planning, spatial analysis, and “AHP” grew in frequency from 2016 (that is, in the last 5 years analyzed).

In addition to quantifying each keyword separately, we also analyzed the relationship between them in order to point out groups that could be interpreted as subthemes that represent specific research fields. This time, we generated a map (Figure 3.3) capable of highlighting the different themes in the domain of knowledge of SA supported by GIS. The map is divided into four quadrants, starting from two axes (X, Y). The X-axis indicates centrality: the degree of interaction of a cluster compared to other clusters, suggesting the importance of a theme. The Y-axis indicates density, meaning it can be understood as a measure of theme development (internal strength) [37].

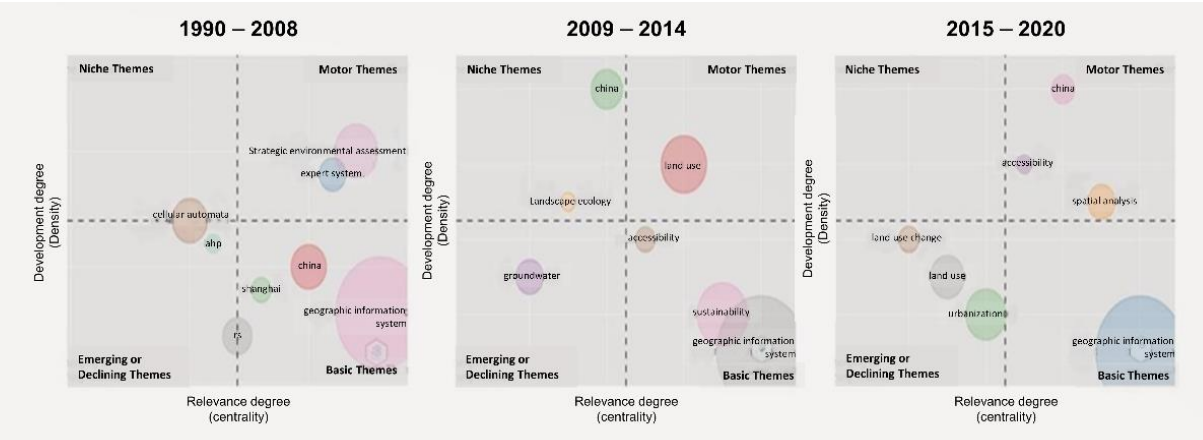

Figure 3.3 Thematic maps of keywords 1990–2020.

The themes inserted in the upper right quadrant have high values of centrality and density, thus, they are important for the structuring of a research field. In this way, they are identified as motor themes. In the lower right quadrant, the basic themes are presented: general topics that can be transversal to different areas of the research field. In the lower-left quadrant are emerging or themes that are declining due to their weak development; they have low centrality and density. Top-left quadrant themes are known as highly developed and isolated themes, meaning they are of limited importance to the field [37].

The total period of analysis of publications (1990 to 2020) was divided here into three timeframes. This is because, as can be seen in Table 3.1, there was a change in behavior in the number of publications from 2008 onwards, with growing increments until 2014, reaching almost 50% of all publications. Thus, the years spanning 2015 to 2020 represent the other half of this indexed research corpus.

Table 3.1 Quantification and characterization of keywords 1990–2020.

Time Frame	Total Publications	%	Author Keyword	Average Keyword per Doc
Until 2008	323	18.77	862	2.7
2009 to 2014	441	25.62	1468	3.3
2015 to 2020	957	55.61	3100	3.2

To identify the themes, we used only the keywords with a frequency equal to or greater than three occurrences, making it possible to identify the most representative themes. In this way, the detection of thematic clusters takes place with greater robustness, and they are identified with the most frequent keywords.

In the initial time frame (1990 to 2008) the tool individualized eight clusters. A single cluster, which configures the environmental themes, appears with high centrality and density, represented by the keywords "environmental impact assessments" and "strategic", characterizing itself as the driving theme of this first period. Among the basic themes, three clusters appear: the largest of them is formed by keywords that deal with the methodological process ("GIS", "remote sensing", "decision support systems"), general theoretical concepts ("sustainable development", "sustainability"), and objects of study ("land use"); the other two basic clusters are represented by the keywords "China" and "Shanghai", with lower centralities. Two themes appear as emerging in this field of research. Thus, the methodological processes that perform processing of satellite images from automated cell modeling have less centrality and greater isolation, but are still dealing with topics related to applied methodologies. The keyword "AHP" appears as an emerging model of multicriteria analysis in the evaluated publications.

The subsequent time frame (2009 to 2014) presents seven individual clusters. During this period, themes related to land use mapping are strongly connected to risk assessments and present themselves as driving themes in the research field. Among the basic themes, we perceive the continuity of those identified in the first analyzed period. However, the theme "accessibility" presents itself with a methodological character linked to the application of AHP, which migrates from an emerging condition to a theme of high transversality to different areas. Thus, a single cluster appears as an emerging theme represented by the keywords "groundwater" and "sustainability indicators". The cluster that is represented by the word

“China”, which in the initial period appeared as a basic theme, now presents itself as a very specialized theme. Another cluster that is also characterized by its isolation in this period is represented by the keywords “ecological footprint” and “ecosystem services”, with low centrality.

In the third and last time frame (2015 to 2020) seven clusters are individualized. The cluster “China” now appears as an engine theme in this field of research. Two other themes present high density and centrality. The methodological theme represented by the keyword “spatial analysis” has a strong relationship with systems linked to “ecotourism” and “renewable energies”. With high density, but still with medium centrality, the theme “accessibility” appears, with a strong presence of the keywords “Sustainable Development Goals” (SDGs). This cluster has been a driving theme for this field of research since 2015. We highlight the AHP methodological process, which initially appeared as emerging, migrated from 2009, and remains as a crosscutting theme until the final period of analysis. Themes related to the analysis of land use, ecosystem services, and urbanization lose centrality and density and this configures them as themes in decline.

3.5 Discussion

The works in SA that are supported by GIS have, historically, an approach mostly focused on the environmental dimension, but which present a global trend of changing focus to assessments that observe the premises of the SDGs, that is, characterized by multidimensionality, so that the spatial variable starts to incorporate not only the environmental dimension but also the social and economic ones.

These findings could be observed from the results obtained in the thematic mapping, where the behaviors of the themes were observed through the relationship between the authors’ keywords in the three time periods analyzed (Figure 3.4), making it possible to trace the evolution in the time of the research on SA supported by GIS.

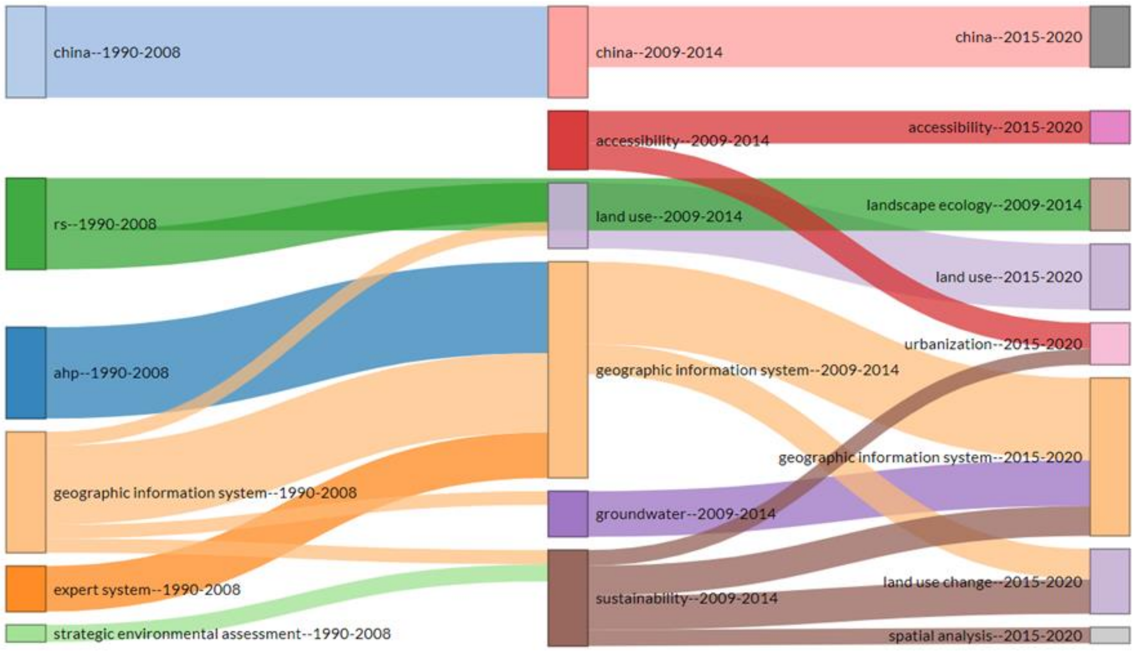

Figure 3.4 Map of behavior and thematic evolution.

Therefore, we observed that initially, the questions that permeated the studies were mainly about research focused on environmental assessments. At that time, GIS was understood as a tool that favored this type of study due to its ability to integrate data and carry out spatial assessments that identify impacts on the environment [40]. In addition, works that were concerned with the study of urban planning emerged and used automaton cell modeling as a methodology together with remote sensing techniques and products. Studies that apply multicriteria decision analysis models, especially AHP, which emerged as a topic of strong centrality, also stand out.

From 2009 onwards, there was a greater variation in the themes addressed in the works, and four movements emerged that best characterize this following period:

1st movement: The basic themes that appeared together with GIS are dismembered and come to appear more prominently. For example, the use of the term “sustainability” starts to relate more strongly to “urban areas”, specifically to the studies of urban sprawl from the mapping of changes in land use in cities and assumes a transversality role among other topics.

2nd movement: China is no longer a basic topic and starts to act as a specialized subject as it becomes strongly linked to studies on the valuation of ecosystem services, and mainly works that assess the balance between supply and demand through the ecological footprint methodology. It is noteworthy that China accounts for more than a third of all publications surveyed, and this helps to explain its emergence as a research topic.

3rd movement: The works that addressed environmental assessments, and which previously assumed the position of the main engine of this field of research, give way to risk assessment studies, especially hydrological ones [41,42] and vulnerability to natural disasters [43] is frequently permeated by the use of GIS in land use mapping.

4th movement: Some studies emerge which are focused on the use of multidimensional sustainability indicators, applied to urban [44], rural [45], and environmental sustainability, are related to transport activity [46] among other themes.

The division between themes has intensified in recent years. Despite this, we highlight two moments that, in some way, are interconnected, and that well define the directions taken by the research in SA supported by the GIS between the years 2015 and 2020. At first, we perceive the highlight of the contextualization of the Sustainable Development Goals (SDG) of the 2030 Agenda (Transforming Our World: The 2030 Agenda for Sustainable Development) as one of the main driving themes in this period. At the same time, the use of spatial analysis has high centrality, which indicates the current use of a GIS-based approach [47–49]. In a second moment, we noticed that the studies focused more specifically on mapping land use and its changes, as well as those dedicated to the valuation of ecosystem services, decreased in centrality, indicating that they were taking a path of decline in research that deals with the SA supported by the GIS.

These perceptions strongly indicate that, even if there are previous publications that have addressed sustainability from the integration of different dimensions, it is from 2015 that the use of the term "sustainability" intensifies the application of socio-ecological variables in order to assess environmental, social, and ecological performance. This period coincides with the expansion of the debate on sustainable development after the creation of the 2030 Agenda, which introduces 17 SDGs along with 169 related targets [50].

Therefore, our results corroborate what Estoque [51] exposes: the demonstration of the application of earth observation data in the production of sustainability indicators and sub-indicators, or even the use of GIS as a SA platform where the entire assessment process takes place geospatially, from the insertion of indicators, weighing, normalization, and aggregation, as proposed by Graymore et al. [52] and Boggia et al. [53] for regional analyses. This may also indicate a reflection of the versatility of GIS, which enables multi-thematic and multi-tasking performance.

3.6 Conclusions

This paper started from the consideration that still the role of GIS in the development of SA has not been fully explored and that, conversely, understanding the subject areas may instead improve their use. Understanding therefore the development and evolution of research areas carried out through a bibliometric approach can be a valuable contribution.

Some studies on the subject of sustainability, as well as its evaluation processes, have pointed to the use of GIS as a trend. However, it was still unclear how geospatial tools have contributed in this context, as well as their future potential. The bibliometric analyses carried out in this study were able to demonstrate that, despite the temporal dynamism of the themes addressed in the works that involve SA and the application of GIS resources, strictly environmental themes are predominant. This reflects the conceptual confusion around sustainability, a topic discussed extensively in several scientific works. Thus, we can conclude that, for the most part, evaluations are observed that consider the use of one-dimensional or strictly biophysical indicators.

However, from the year 2009 and especially in the last analyzed period (2015–2020), the results show that there is a trend of the multidimensional approach and that the SDGs, discussed worldwide in recent years, have become guides for SA. This may indicate a direction for future works in this field: to adopt the use of GIS techniques not only in spatialization but also in the generation of environmental, social, and economic sustainability indicators. In other words, these multidimensional indicators can carry, in addition to environmental and socioeconomic information, also geospatial information, where their geographic positions are fundamental in the assessment of progress towards sustainability.

Therefore, there is the realization that the GIS, which initially supported the SA as a mapping tool associated with environmental issues (in which spatialized data were mostly used to determine the use and occupation of the land) gives rise to other application possibilities, mainly due to the evolution of geospatial techniques and tools associated with other sciences. These new perspectives develop in parallel with the global discussion on sustainability, that is, the evolution of use, and even technology, follows the evolution of the concept of sustainability.

3.7 Study Limitations/Strengths

Scopus is the largest database that indexes a greater number of abstracts and citations from peer-reviewed literature than other scientific research databases [34]. However, not using other databases can limit the scope of the research.

Furthermore, this work analyzed a total of 1721 articles, providing a systematic analysis of the authors' use of keywords, bringing important information about the sources that stand out to be consulted, and pointing out directions for future work.

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4 OPERATIONALIZING THE REGIONAL SUSTAINABILITY ASSESSMENT BY INDICATORS

Abstract: The regional scale has the potential to reduce the distance between the population, decision-makers, and stakeholders in general, which facilitates interaction between them and favors an evaluation process capable of indicating more sustainable and more effective paths. However, the regional sustainability assessment is not an easy task, and some challenges make this activity more challenging. Among the main challenges are the availability and accessibility of disaggregated data that describe the region, the effective participation of stakeholders in the development of indicators, the periodicity of the sustainability assessment, and, in particular, the integration of the spatial dimension in the assessment process. Evaluating sustainability spatially implies recognizing regional heterogeneity, bringing to decision-makers the perception of the need for sustainability strategies that are not homogeneous. In addition, communication based on a spatial representation (maps) contributes to society, achieving a better understanding and interpretation of the results. This chapter presents the challenges and practices concerning the regional sustainability assessment.

Keywords: Regional sustainability, Sustainability assessment, Sustainable development.

4.1 Introduction

The discussions about the need for conceptual clarification around sustainability and sustainable development (SD) are still emerging and are proving to be a great challenge (Kuhlman & Farrington, 2010). However, the definition that sustainable development is characterized as “development that meets the needs of the present without compromising the ability of future generations to meet their own” is widely accepted (WCED, 1987). This is an interpretation that perceives sustainability from pillars representing the ecological (or environmental) system, the economic system, and the social system, although it is a difficult approach to identify its origin and questionable theoretical foundations (Purvis et al., 2019).

Although there are different currents of thought, this is a precept that favors sustainability assessments (SA) because it can meet the individual capacities of the participants in the assessment process, in addition to favoring the use of data that are often collected from this fractioned vision of the environmental, socioeconomic systems (Ginson, 2006) and sometimes with the insertion of a fourth dimension, for example, the institutional one (Purvis et al., 2019).

Although they diverge in the number of dimensions in which the human-nature relationship is expressed, there is a convergence in the understanding that, in order to achieve development on the path to sustainability, there is the need to carry out assessments that are able to "specify a limit between what contributes to sustainable development and what does not" (Sala et al., 2015), and from there, being able to support decision-making processes, whether at a strategic or operational level (Ramos, 2019).

There is a wide range of methods and tools capable of evaluating and reporting the SD; however, the use of sustainability indicators (SI) represents one of the most popular instruments used to translate the sustainability assessment (SA). Assessments that use SD-oriented SI seek to incorporate and integrate these different dimensions; therefore, these and other factors imply not only a series of opportunities but also challenges (Ramos, 2019).

Among some challenges that can be identified in applying SI at all scales are the methodological processes of developing indicators, weighing methods (weighting), and data availability and reliability (Verma & Raghubanshi, 2018). Other challenges can be encountered depending on the scale applied.

In a regional sustainability assessment (RSA), for example, Wallis et al. (2007) highlight obstacles such as the selection of indicators that are really in line with the sustainability vision of the assessed area, the need for inclusion and encouragement of stakeholder participation, the accessibility and condition of the data that feeds the assessment, and the unavailability of georeferenced data. While Graymore et al. (2008) mainly highlight the unavailability of data that are appropriate to the assessment scale, Coelho et al. (2010) state that an RSA should dialogue with the objectives of local and national developments, and that is why it needs to be an assessment that allows for the interaction between the different scales, but that this is still an underexplored issue.

Based on the above, we can infer that a regional sustainability assessment (RSA) requires even more specific observations. In an attempt to contribute to this debate, this chapter aims to discuss different operational particularities of the RSA, pointing out methodological paths to overcome challenges that we consider essential in the operationalization of the evaluation and that aim to fill some identified gaps, namely, the multilevel interaction, where the indicators dialogue in a cross-scale approach; the inclusion of stakeholders in the selection of indicators, from a broadly participatory perspective; and the geospatial approach in RSA.

Thus, this chapter is organized as follows: after the introduction, in which we present an overview of the concepts and gaps that remain in the RSA processes, we continue with a contextualization of different sustainability understanding (Sect. 4.2) that will support the multidimensional SD approach (Sect. 4.3). In Sect. 4.4, some challenges and particularities inherent to SI applications in RSA found in the literature are raised. Section 4.5 points out some methodological solutions proposed by different studies that aim to overcome three challenges which we point out as essential for an RSA. In Sect. 4.6, some final considerations are presented.

4.2 Sustainability: A Multidimensional Concept

After analyzing a vast body of literature on sustainability, Kuhlman and Farrington (2010) concluded that the concept that defines it remains to be clarified. Thus, the conceptual definition of sustainability, or sustainable development (SD), remains one of the main debates among thinkers on the subject, and this causes many and different concepts to be developed. Bolis et al. (2014) emphasize that the complexity surrounding sustainability is even more significant as its conception can mean many things to different people and that this plurality of meanings tends to increase over time.

However, there is a definition of sustainable development that is widely adopted worldwide, whether in academic or political literature (Purvis et al., 2019) and has been popularized by the United Nations as one that strikes a balance between the current generation's needs and those of the future generations (WCED, 1987). But Janouškov (2018) adds that this definition can serve as a springboard for a variety of interpretations, because it is accompanied by imprecision, ambiguity, and, at times, contradictions. Sala et al. (2015) corroborate this view and draw an analogy between the concept of SD and social justice, inferring that both are value-laden concepts and therefore capable of generating different perspectives and perceptions.

To illustrate the theoretical complexity surrounding the topic, we have identified here four different approaches in which sustainability can be interpreted according to Patterson et al. (2017), namely, ecological interpretation, economic interpretation, thermodynamic and ecological-economic interpretation, interpretation through the approach of public policies, and the theory of planning for sustainability. Although conceptually distinct, these interpretations have in common the focus on valuing natural resources as instruments for human well-being (Seghezzo, 2009).

This anthropocentric view of sustainability permeates the majority of conceptual debates and is premised solely on attention to human values and humanity's well-being, which means that policies involving the environment are directed toward this end (Seghezzo, 2009). Despite this, other currents of thought have also directed the sustainability discourse toward a more holistic worldview, also recognized as "ecocentric," in which nature would have an intrinsic value, that is, it is directly related to human interests (Ramos et al., 2020; Seghezzo, 2009).

At the same time, some less radical strands of thought discuss sustainability frameworks that involve spatial, temporal, and individual characteristics that may be disconnected from economic growth, a quality ecological environment, and even social justice (Seghezzo, 2009). This approach focuses mainly on the criticism and discussion of the overestimation of the the pursuit of economic dimension in sustainable development.

However, such perspectives are far from the anthropocentric understanding of sustainable development pointed out by the United Nations from the report "our common future" (Brundland report), through Agenda 21 and more recently in Agenda 2030, in which economic growth can be seen as a solution to ecological and social adversities (Purvis et al., 2019). This description of sustainability in which economic, social, and environmental systems are seen separately but interconnected is prevalent (Purvis et al., 2019). We can find in the literature different nomenclatures for this triple relationship, such as "pillars of sustainability" (Ginson, 2006), dimensions (Stirling, 1999), or components (Stirling, 1999).

It appears, therefore, that the most widely accepted and disseminated conceptual and methodological path, whether in academic literature or in the political sphere, perceives sustainability from three bases that represent the ecological (or environmental) system, the economic system, and the social system. This conceptualization, sometimes called the triple bottom line (TBL), begins explicitly in 1987 with Barbier's (1987) description of three sustainability system objectives (biological, economic, and social) and gains strength after strong corroboration of the United Nations in its reports thereafter.

This understanding then becomes widely accepted for different scales. In line with this anthropocentric view, Smetana et al. (2015) define regional sustainability (RS) as the capacity that a system has, on a regional scale, to support current socioeconomic and environmental conditions and which provides, or enables, future development, or, in the worst case, maintenance of the current state. Still in agreement with this perspective, Graymore et al. (2008) add that this concept implies that the population must live respecting the limits of social, economic, and environmental systems, in order to guarantee the equitable sharing of resources in an intergenerational way.

If we consider the different interpretations of sustainability listed by Patterson et al. (2017), we see that Smetana et al. (2015) define RS based on an alignment with the public policy approach and the theory of planning for sustainability, that is, it is a concept that, structurally, envisions a type of "balance" between the factors that are composed of multidimensional aspects. Therefore, it is a sustainability that, in order to be evaluated, criteria that involve human interaction and the environment in different dimensions must be considered.

4.3 Multidimensionality That Favors Assessment

This multidimensional approach, however, has an important advantage when it comes to assessing sustainability. In this sense, Ginson (2006) considers that this separation into different dimensions may come from the individual capacities of specialists who participate in the evaluation process, and it confluences with the way in which much of the data is collected separately, considering such categories, in addition to the institutional structure of governments, which generally takes place in a sectorial manner.

However, it should be noted that, although there is a broad TBL approach in several SA works, some studies consider the insertion of additional dimensions, such as institutional, cultural, and technical (Quadruple Bottom Line - QBL) (Purvis et al., 2019). Among the examples mentioned, the institutional dimension, or also called governance, has the potential to support decision-making that actually leads the evaluated areas to the path of sustainability. This is because the inclusion of governance among the sustainability dimensions can provide insight into sustainability areas that, in other TBL approaches, may be neglected, such as community involvement, transparency, accountability, and ethics (Aliba, 2017).

Whether using TBL or QBL approach, achieving sustainability requires obtaining assessment methods that can reliably measure sustainability, in order to enable well-informed planning and decision-making (Graymore et al., 2010), that is, it must translate the relationship of the systems that involve society in nature to decision-makers, in order to help them determine which actions should or should not be taken, related to a certain area (Kates, 2000), and this is not an easy task.

One of the most accepted understandings of sustainability assessment (SA) is the idea that it is possible to measure the sustainability state of an object of analysis, be it a nation, region, municipality, or company, in a multidimensional context involving the interaction between human activities and the environment. This concept can be expanded, as explained by Ramos (2019), because SA is widely used based on two distinct but complementary objectives, that is, if on the one hand, it can characterize the state of sustainability of a situation currently implemented, on the other hand, the evaluation can predict the possibilities of the implementation of some future activity.

Therefore, whether on a macro (strategic) or micro (operational) scale, this measurement must consider multidimensional data that vary according to the evaluation objectives. O'Connor (2010) adds that SA should also pay attention to the types of concepts that guide the assessment, the framework adopted, and the set of data that may be relevant to support the decision.

The concerns pointed out by O'Connor are part of a set of characteristics that differentiate an SA from a "purely" integrated assessment, that is, they must be conjectures that go beyond the simple integration of dimensions but that have sufficient scope and robustness to leverage effectively sustainability, going beyond the simple assessment of its progress. Sala et al. (2015) bring this important theoretical discussion about the fundamental differences between SA and other assessment methods and point out that, given the epistemological uncertainties of sustainability, it is a concept potentially influenced by personal views, it is deeply related to cultural perspectives, featuring a political nature, not being thus possible to separate the evaluation process of the effective involvement of stakeholders at all stages.

Although there are several methods for the SA, Sala, Ciuffo and Nijkamp (2015) also point out that the most used tool is the use of sustainability indicators (SI), thus obtaining a prominent role in the evaluation that involves decision-making. It is essential to have an assessment that actually reflects the specifics of the area studied, inevitably passing by the process of selecting the indicators to be applied. However, this is still one of the greatest challenges for SA.

4.4 Regional Sustainability Assessment: Operational Challenges

Verma and Raghubanshi (2018) point out several challenges in using SI for SA. According to these authors, the challenges are divided into two categories, internal and external. In the context of internal challenges, problems such as the methodology used for the development of indicators, methods used in weighting, and the application of excessively complex or simplistic methods are listed. In the context of the external challenges are the lack of data, resistance on the part of government agents to implement the indicators, lack of consensus, and lack of comparative analysis. According to the aforementioned authors, these are some common problems in the implementation and incorporation of indicators in decision-making.

In this sense, Ramos (2019) brings a discussion that aims to identify new frontiers in the use of SI from an analysis that qualifies a set of challenges and opportunities identified in the literature, expanding those already pointed out by Verma and collaborators. In this study, Ramos identifies, for example, that the limitations related to data availability, the improvement in the criteria for selecting indicators, and the use of remote sensing technologies and data are highly relevant. These are examples of issues related to the operationalization of SI at all scales. In a regionalized context, these and other difficulties inherent to the assessment scale emerge. Below, we highlight three works that observed some obstacles at the regional scale.

Wallis et al. (2007) point out some challenges found in an RSA in Vitoria city – Australia southwest region and that can easily be faced in other regions of the world, such as the selection of indicators that really reflect the sustainability vision of the evaluated area; the availability, accessibility, and condition of the regionalized data that feed the assessment; the deterioration of confidence in the data due to incompatibility of time and collection techniques; the absence of qualitative data that could more appropriately reflect local values; and the absence of in-depth knowledge of the interdependencies of natural and human systems in the region.

Graymore et al. (2008) analyze the effectiveness of five sustainability assessment methods at the regional level and demonstrate that none were fully effective, mainly due to the absence, at a regional scale, of much of the data needed to carry out the assessment, in addition to the weakness in the aggregation process based on the integration of indicators. Based on this observation, Graymore et al. (2010) propose an assessment method that is applicable at a regional scale, based on the concept of human support capacity, and that is capable of producing well-informed decision-making, supporting the implementation of managing action strategies aimed at regional sustainability and that would facilitate awareness by the community about sustainability, enabling the inclusion of stakeholders in the transition. However, they also found limitations, mainly regarding the availability of data at a regional scale.

On data-related limitations, Wallis et al. (2007) point out the unavailability of economic, social, and even biophysical data that are georeferenced and that adequately meet the spatial and temporal scale. In their studies, Wallis and collaborators recognize the importance of using geographic information systems (GIS), which are a powerful tool in the collection, storage, and management of geospatialized data used in the development of indicators, and point to the possible visual impacts caused on the managers and decision-makers, who would facilitate the identification of potential intervention sites.

4.5 RSA Operational Gaps and Methodological Pathways

In this section, we will point out three different methodological pathways that aim to fill some gaps in RSA. First, we indicate a guideline for the regional sustainability indicators' interaction process with the local and supra-regional levels, in order to enable comparative analyses. Afterward, we will discuss the importance and a brief path for the operationalization of stakeholder involvement in the indicator selection process. And finally, we will discuss the geospatial approach in RSA, where the spatial dimension is presented as a key element, and the application of geospatial techniques, tools, and data can be essential.

4.5.1 Multilevel Interaction in the RSA

The classic concept of region describes it as a geographic area, which can be the result of grouping processes determined by the state, aiming to organize its territorial base with a view to public policies. This is what Cooke (2006) translates when he defines the region as an administrative division of a country, below the national level, but above the local or municipal level. However, regionality can also be established by natural limits, such as a set of hydrographic subbasins, not restricted to administrative limits. Therefore, it is a grouping of different geographic or administrative units, which may reflect different impacts generated from the relationship of human activities in the nature inserted there.

Therefore, if we think within an ecological context, we can add that this geographic area ends up connecting multiple biodiversity spatial and temporal scales (Brunckhorst, 2005).

However, we understand that this multiscale connection, in time and space, is not exclusive to the environmental system but can also occur in socioeconomic systems. This makes the agents involved in regional governance have a particular SD task, as they are faced with different environmental, social, and economic conditions (Smetana et al., 2015).

And it is in this context of regional heterogeneity that we highlight the importance of RSA. This must be a process capable of going beyond an assessment between the places that are inserted in the region, but it must also allow a comparison of the sustainability performance between different regions, in order to promote the interaction between different spatial scales. However, to satisfactorily carry out this interaction of scales, it is necessary to have specific RSI, and which contain national and local relevance (Coelho et al., 2010). Therefore, here we have two distinct situations of multilevel interaction, one interregional, in which the evaluation process also looks at other regions, and the intraregional, in which the region is assessed as internal geographic units.

In the first (interregional), it is essential to use SI that provide enough information for a comparison of sustainability to be carried out and thus improve the analysis of asymmetries between different regions. In the second (intraregional), SI common to the localities and that can be adopted by all municipalities are necessary, which promotes competition between them. This approach increases the chances of involving local communities in the regional assessment process. To better clarify how RSIs act in the context of interregional and intraregional interactions, we describe below the main theoretical and methodological directions pointed out by Ramos (2009) and Munda and Saisana (2011).

4.5.1.1 Interregional Multilevel Interaction

To achieve the objective of producing information that enables a comparison of sustainability performance between regions, from a regional/national perspective, it is necessary to have a subset of common regional indicators (SCRI) inserted in the basic RSI set. This subset should be composed of indicators that have as an intrinsic characteristic their availability to all regions within the national governance scope. In this sense, in order to ensure greater consistency in its definition, this subset needs to be established at the national level. Thus, the SCRI will complement the specific regional indicators (Ramos, 2009; Munda and Saisana (2011).

Furthermore, there is also the possibility that each region has its own set of headline indicators that can compose, totally or partially, the national set. The selection of these indicators takes place according to the degree of relevance attributed by the interested parties (stakeholders) at a regional and local level and by the majority of specialists. This set of specialists can be formed by members of the academy, employees of regional agencies, in addition to other specialized professionals, including from other regions, and their participation takes place in the role of a steering or advisory group (Coelho et al., 2010) and will help to identify those indicators that are most relevant to the assessed region.

The headline indicators are very important in RSA because they have a high power to communicate sustainability to decision-makers, in addition to providing information that is particularly useful to nontechnical stakeholders (Ramos, 2009).

4.5.1.2 Intraregional Multilevel Interaction

If we analyze the composition of the SSI set, from the perspective of the regional/local relationship, we will see that it is necessary to define a subset of common local indicators (SCLI). This makes it possible to analyze the asymmetry between the places that make up the region. To select this subset of indicators, it is necessary to take into account the strategic instruments of the municipalities, based not only on common local resources and characteristics but also on shared objectives and goals. Thus, this set of RSI can also be used as a monitoring tool for these strategic instruments, such as a regional spatial project through land-use planning (Mascarenhas et al., 2010). However, Wallis et al. (2007) warn that, in order to access local knowledge, these main indicators must be also composed of qualitative data because they can truly represent local values. The obstacle, in this case, remains the availability of this type of information.

Having overcome this difficulty, it is clear that the existence of SCLI facilitates the formulation of appropriate public policies. And this happens as it becomes possible to identify the vulnerabilities and risks to ecosystems, social communities, and economic categories for each location. Thus, the relevant characteristics and actions taken in one municipality can be compared with their counterparts in other municipalities. This will allow local decision-makers to point the strengths, weaknesses, opportunities, and existing threats, as well as discuss and share new ideas, which provides a rich process of mutual learning (Mascarenhas et al., 2010).

This approach of common local indicators in an RSA has two very important skills. On the one hand, it promotes the qualitative and quantitative enrichment of data at a local scale that is also relevant regionally, and on the other, it has the potential to involve local stakeholders in the assessment process. This creates an interactive process with communities (Coelho et al., 2010).

The organization of the core set of indicators and the intra and interregional ISR subgroups are illustrated in Figure 4.1.

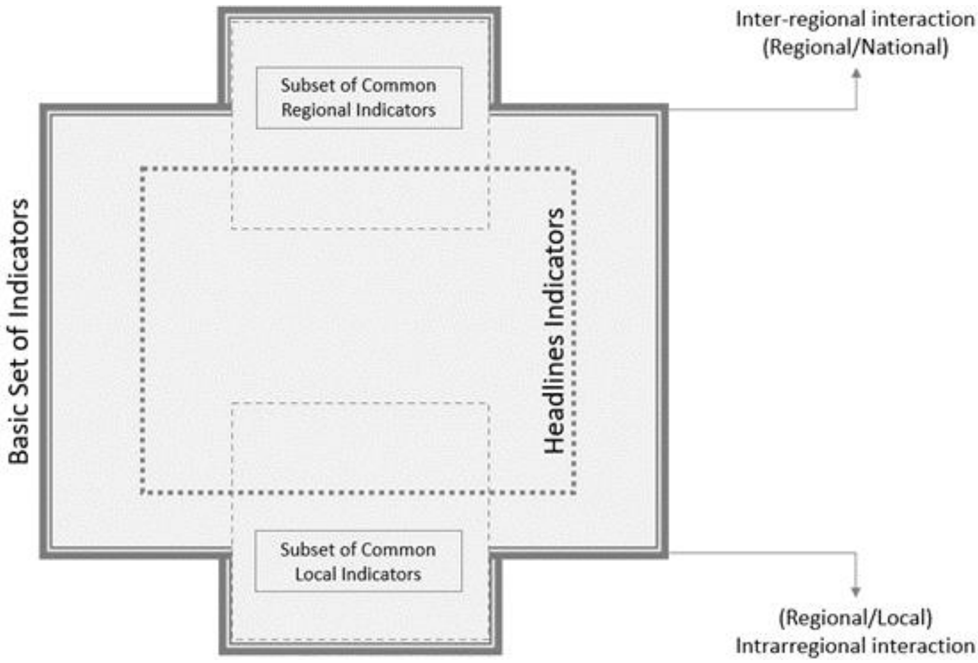

Figure 4.1 Schematic composition of the core set of indicators

4.5.2 Stakeholder participation in RSA

Public participation in RSA processes using indicators plays a key role. Ramos (2009) highlights the relevance of this participatory approach not only by experts but also by stakeholders in general. And he adds that this participation is especially important at regional and local scales because it is precisely at these scales that there is greater proximity between the community, experts, and decision-makers, which can represent a simpler and more effective interaction. To better explain how this interaction of stakeholders in RSA can take place, we will address some aspects pointed out by Coelho et al. (2010), among them, the identification of who these stakeholders are and how they are organized, where public participation can effectively occur, the tools and instruments to operationalize this participation, in addition to the advantages of adopting this practice.

Coelho et al. (2010) identify three main stakeholder groups that in some way may be included in the participation process: (i) national, regional, or local public administration agents, (ii) private groups representing companies or industries, (iii) and the general public with representatives of the community as well as of nongovernmental organizations (NGOs). It is noteworthy that, sometimes, a fourth group can act with a consultative character, formed by specialists.

Undeniably, stakeholders can be a viable source in identifying the most relevant and priority regional and local sustainability issues, which is why public participation in the selection of general indicators as well as the headlines indicators is so important. Furthermore, integrating the community also allows for a voluntary data collection movement (Coelho et al., 2010). Obviously, this process needs to be coordinated in order to achieve good reliability of the collected data.

Therefore, it is necessary to provide means, or techniques, that enable this participatory process of selecting indicators where regional and local actors can interact in order to collaborate. Among some instruments, we mention workshops and seminars, which can be open to the participation of all stakeholders. In addition, some thematic meetings can take place where more specific stakeholders participate, such as NGOs and public and private institutions. In this case, they are carried out through sectorial meetings, working groups, and round tables (Ramos, 2009).

In general, the participatory approach is of paramount importance to create an interactive movement with communities, inserting them into the RSA process from the beginning. Thus, it is possible to obtain a set of indicators that are in fact relevant and that measure more precisely what is regionally significant.

4.5.3 Geospatial Approach in the RSA

We highlight here some important aspects that must be considered in an RSA from the perspective of geospatial characteristics inherent to the regional scale, where the heterogeneity of resources, in all dimensions, is intrinsic. We want to demonstrate that, if on the one hand, the spatial characteristics of the regions can pose new challenges, on the other hand, the application of geospatial techniques, tools, and data can represent new opportunities.

As already mentioned, the determination of indicators that are common at different scales can favor the comparative analysis of sustainability performance within and across regions. However, Smetana et al. (2015) warn that the differences between the state of regional sustainability will depend on the quantity and quality of available resources and that the region's spatial characteristics, namely, shape, size, and physical quality of the environment, can be determining factors in the result.

Here, an important challenge is highlighted, which is the definition of the limits of the region in which it intends to assess. An RSA that considers a region characterized by administrative boundaries (Cooke, 2006) may encounter difficulties for comparative analyses. This is because the regions will have different sizes, and it is to be expected that the larger the size, the greater the number of resources, for example. Furthermore, the spatial distribution of these resources must be considered because they are likely to be unevenly distributed. The georeferencing of the resources evaluated can favor a localized understanding of the problems that lead the region away from the path of sustainability.

We can exemplify from the mapping of land use and occupation patterns that can be seen as a key element for RSA. The work of geospatial identification of land use in a region is of great importance, for example, to verify the existing relationship with areas of degraded soil, or with the imbalance in the availability of water resources, or even with the loss of biodiversity (Smetana et al., 2015), that is, they are extremely important information for RSA. Thus, what can be seen is that, whether due to the heterogeneity in the spatialization of resources, or concerning the size of the region, or how the limits are arranged, the use of geospatial data is an essential way to obtain more effective results.

4.5.3.1 Spatialization of Data for RSA

As mentioned above, we understand that for a SA focused on SD, different dimensions involving human actions and the environment must be addressed in an integrated manner. These different dimensions are represented by SI which in turn are reached from environmental and socioeconomic data. However, due to the nature of the information, these data may have different collection methodologies, causing them to be represented in different spatial contexts.

To illustrate the abovementioned situation, we can mention the measurement of the gross domestic product (GDP) inserted in the socioeconomic dimension (although widely criticized), and which is, for the most part, scaled to municipal scales or larger. The same is true for demographic data, income and education, unemployment, housing, among others, while environmentally important data, such as measuring environmental noise, for example, inevitably occurs at a local level. Therefore, it is evident that the assessment scale has a fundamental role in choosing the indicators to be used.

However, the characteristics and particularities of data spatialization and its use in RSA go beyond that. The European report Planning System for Sustainable Development, by the Ministry of Environment and Energy of Denmark – PSSD (Hansen, 2001), makes some observations that are technically important for discussing the operational challenges that exist when developing SI for RSA concerning the geometric shape of representation. It is well known that some socioeconomic and environmental data are collected from a relationship with polygonal entities; however, there may be intrinsic structural differences between them. In other words, if, on the one hand, social and economic data are almost always collected considering spatial units that have been administratively defined, on the other, environmental data come from a specific spatial variation.

Therefore, there may be a conflict in the way in which these data are geometrically represented, featuring another methodological challenge which is the crossing of data to determine the performance of regional sustainability. To represent this situation, we return to the example of GDP, which is represented polygonally (city, region, country, continent, etc.), while environmental noise is represented punctually. We observe the same situation between data on land use and occupation (polygonal) and air quality or traffic count (punctual), for example. Despite this, SI are commonly based on statistical aggregations that disregard the spatial distribution of data, restricting themselves to administrative limits (Hansen, 2001). These limits may change over time.

These notes highlight some challenges inherent to the spatial problem in RSA, which can create difficulties for decision-making processes that actually lead to SD. However, some initiatives have been developed in order to provide methodological solutions for a spatialized sustainability assessment, based on the use of geospatial techniques, tools, and products, such as the geographical information system (GIS) and data from remote observations of the earth (Remote sensing).

4.5.3.2 Geospatialized RSA

GIS is a powerful tool that acts from the collection, storage, processing, and evaluation of spatialized data, in addition to providing an efficient visualization of results in a geographic context. Remote sensing, on the other hand, can be understood as a science that, in general, acts in the observation of the earth through orbital sensors that record electromagnetic energies from different fractions of the electromagnetic spectrum, generating digital images in different spatial, spectral, radiometric, and temporal resolutions.

These two areas of knowledge are fundamental for obtaining and processing spatialized data that are potentially needed in RSA. Next, four geospatial approaches in SA will be cited that provide, from previous experiences, methodological proposals that aim to fill some gaps, already pointed out in the literature, related to the spatial problem in RSA.

Graymore, Wallis, and Richards (2009) generated a regional sustainability index from a decision support model based on GIS, which can also be identified as a spatial decision support system (SDSS). This work consists of a SA on a regional scale, in which the grouping of a set of subbasins was considered, that is, these are limits that were defined naturally and not by administrative standards. The method proposed in this work performs a weighting and aggregation of indicators with the support of a decision support system, which, according to the authors, imposes an objective character on the process.

The application of an SDSS in an RSA proved to be potentially useful in supporting decision-makers, especially in the step referring to the communication of the results obtained. The combination of geospatialized data with multicriteria decision models allowed illustrating the results through maps that make it possible to spatially illustrate the variation in sustainability between the subbasins that make up the region. This can provide decision-makers with the opportunity to prioritize, in a localized way, the subbasins that need initiatives that aim at sustainability, in addition to other management actions involved in decision-making. In addition, this geospatialized method allows you to visualize any changes in the performance of the sites that make up the region, as assessments are repeated over time, and this will support the assessment of the effectiveness of sustainability strategies and plans.

As in the previous example, the work developed by Boggia et al. (2018) proposes the application of an SA model based on spatial multicriteria analysis. However, they differ in that they propose a Multicriteria Spatial Decision Support System (MCSDSS), with complete integration between geospatial data and multicriteria analysis through a GIS interface. This means that, for its use, only one tool must be manipulated, which simplifies the process and enables a greater range of use among evaluators and researchers.

The model proposed in this work allows analyses at any level (local, regional, national) regardless of the definition of limits (natural or administrative) and allows the use of multidimensional indicators. These sustainability indicators are displayed in a table (attributes table) that is associated with each of the geographic features corresponding to the various locations that, interconnected, form the geographic space of the region. Thus, sustainability indexes are generated for each dimension considered, as well as an overall sustainability index. Regarding the communication of results, this method proposed by Boggia et al. (2018) generates, in addition to the graphics, different maps where each dimension can be evaluated separately, or in a single map, where the spatial differences that will translate the region's heterogeneity can be identified, allowing a comparison between the places that make it up, in addition to allowing the identification of areas where measures are most needed.

This approach proposed by Boggia et al. is promising for regional assessments as it is able to identify the spatial differences in the region, pointing out the need for sustainability strategies that are not homogeneous across the national scale, that is, it is capable of identifying demands specific in different areas.

The next example differs from the others in terms of the methods and data used. Vitor et al. (2020) develop a sustainability index on a regional scale, defined by a set of subbasins. For the composition of the index, indicators that contemplate the environmental, social, and economic dimensions of sustainability were aggregated; however, the results obtained are not limited to administrative limits, nor the natural limits of the subbasins, but represent a spatial interaction that goes beyond of discrete objects and starts to adopt a characteristic of continuous fields. This was made possible by using geoprocessing tools to combine census data and information resulting from remote sensing image analysis.

The map resulting from the analysis made by Vitor et al. (2020) provides information on the spatial sustainability of the region in order to identify priority areas for initiatives to be taken on the path to sustainability in an even more specific way, due to its geographically specific character. Thus, the approach proposed by these authors advances in the discussion of the spatialized representation of regional sustainability performances because it allows the obtaining of spatialized indexes that go beyond administratively or naturally defined geographic borders; however, it presents an important limitation insofar as the number and the types of indicators are predefined, not allowing for more efficient processes of varied selection of IS.

The last example to be cited is a methodological proposal of aggregation and disaggregation of the collected data's spatial patterns that will compose the SI. The document

PSSD (Hansen, 2001) guides a spatial approach to data that is different from the other examples cited. Regarding the use of GIS in SA, they emphasize that it is assumed that indicators have spatial characteristics associated with a specific scale, that is, a geospatialized indicator requires its own reference area. Sustainability indicators that make up the socioeconomic dimensions are commonly related to administrative boundaries (e.g., municipalities, counties, states) or, rarely, to physical boundaries (e.g., watersheds). Despite the possibility of processing that allows interchangeable changes between these two types of borders, data collection takes place respecting the original reference areas.

Additionally, we can consider some indicators that may have arbitrary spatial units, inherent to the scale adopted at the time of data collection, as in the case of biodiversity, for example. Hansen (2001) guides such cases the use of the GRID method.

This means that the authors propose a change concerning the adoption of geographic features, that is, no longer representing space by polygonal objects, and adopting a subdivision of space into discrete squares called cells, for which values are stored. A cell can be understood as a uniformed unit that will represent a defined area on the earth's surface (such as a square meter), but which will change in size depending on the purpose of the assessment.

The GRID method approach allows that data that was originally collected punctually can be represented by one or a few contiguous cells, while data collected polygonally can be represented by a range of cells. Among the advantages of this method are the fact that these cells do not change in size over time, unlike what can happen with administrative boundaries, and this makes the use of GRID a more appropriate system in change analysis. Another advantage is related to the spatial adequacy of the RSI between socioeconomic and environmental data, which, despite adopting discrete limits, can generate results on a continuous basis. Among the disadvantages are the computational limitations for processing at very large scales, in addition to the challenge of choosing the appropriate cell size.

4.6 Final remarks

It is widely known that SA are essential to support managers and public agents in decision-making that direct the areas evaluated, at different levels, to the SD. In this sense, the use of SI is the most popular tool in assessment processes. However, the regional scale presents several peculiarities, ranging from the necessary cross-dialogue between the scales at the level above and below to the conflict between the spatial patterns of the disaggregated data that are collected.

Thus, in this chapter, we address three factors that we consider to be main in RSA and that deserve to be highlighted: (i) The multilevel interaction, which takes place on a national-regional-local scale, is addressed using regional indicators applied to all regions, allowing for comparability, in addition to a common set of indicators applicable to all municipalities and assumed for the entire region. (ii) RSA's participatory stakeholder approach, which creates an interactive process with communities and makes the selection of indicators align with recognition of the most important regional issues. This participation of people from the public administration, private groups, and the community, in general, can take place through workshops, seminars, round tables, among others. Finally, (iii) the geospatial approach in RSA. Issues such as defining the boundaries of the regions to be assessed and the spatial distribution of resources must be taken into account in the assessment process. Thus, the use of geospatial data, geoprocessing techniques and tools, and remote sensing products may be unavoidable. More than that, they can be fundamental for having results that actually help in decision-making that effectively lead the regions to the path of sustainability.

4.6.1 Research Limitations

This chapter aims to broaden the debate on RSA constructively by presenting some methods potentially capable of filling some gaps that persist in the literature, especially those related to the availability, adequacy, and feasibility of data that will feed the process of evaluation. However, there is a limitation that the text reflects the authors' point of view by pointing out the methodological approaches they consider essential for the discussion of the topic.

4.6.2 Gaps That Persevere

Despite pointing out some paths found in the literature to provide greater potential for RSA in influencing decision-makers in taking sustainable initiatives, other gaps related to the topic still persist. As already clarified, the participatory approach is fundamental so that the evaluations can portray what is really important for the community inserted in the evaluated territory; however, the persuasion of this need by the stakeholders themselves is still a challenge. The majority participation of some groups in the selection and/or collection of indicators may mean that the assessment does not necessarily reflect the common interests of society.

The use of geospatialized data and products derived from earth observations is still quite incipient compared to the entire period of debate involving SA. Furthermore, georeferenced socioeconomic data is still very scarce. Another very important gap is the lack of studies that assess the perception of stakeholders and specialists regarding spatialized sustainability assessments. In this sense, some questions can be raised: do spatialized organizations actually contribute to truly sustainable decision-making? Does the communication step of an SA through continuous spatial feature maps favor punctual decision-making? These questions still need to be answered.

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5 PERFORMANCE TOWARDS SUSTAINABILITY: A REGIONAL ASSESSMENT SUPPORTED BY THE GIS

Abstract: The use of Geographic Information Systems (GIS) has been pointed out as a methodological trend among the various methods, models, and tools applied in Sustainability Assessment (AS). Although AS is carried out at different scales, that is, from operational level (companies, products) to strategic level (regional, national, global), the application of GIS support is pointed out as a more interesting option on a regional scale, as it is where interactions between ecological functions and human activities are most intensely perceived. Added to this is the fact that these evaluations use regional indicators, and this becomes more important when the elaboration of public policies is decentralized to regions or local communities. In this sense, the aim of this work is to broaden our knowledge of the approach of SA on regional scales, proposing and applying a geospatialized performance assessment framework towards Sustainability. For this, we used a Brazilian metropolitan region as a study area, applying indicators fed by secondary data and generated from remote sensing products, aligned with global goals for sustainable development. In addition, we use a Multi-criteria Spatial Decision Support System model fully integrated with GIS software for processing and analysis. In the end, we generated a performance index towards susceptibility that included different dimensions of the human-nature relationship, through the processing of georeferenced data.

Keywords: Regional Sustainability, GIS, Remote sensing. Multicriteria Decision Analysis, Global Targets for Sustainable Development, 2030 Agenda.

5.1 Introduction

There are several methods to assess sustainability, however, Sustainability Indicators (SI) are among the most used instruments in different scopes of measurement. In addition, these indicators can be applied at different scales, that is, they can range from operational levels (companies, products) to strategic levels (regional, national, global) (Ramos, 2019). In common, these Sustainability Assessments (SA) have as one of the main objectives to reveal what contributes (or will contribute) or not to sustainable development (Sala et al., 2015) and thus support decision-making processes.

However, SA carried out at different levels may present some singularities. While assessments at operational levels aim, for example, to compare products or improvements in the production cycle (Smetana et al., 2015), assessments at strategic levels aim to diagnose society's relationships with nature in different dimensions (areas), and may assist in policy formulation or even disseminate development information to the public.

Historically, SA at a strategic level has been developed at the local and national scales. However, the regional scale has been identified as a more interesting option because it is where the interaction between ecological functions and human activities is perceived more intensely (Graymore et al., 2009), and, although several sustainability indicators have been developed for national and local scales, the regional indicators gain importance when the elaboration of public policies is decentralized to regions or local communities (Coelho et al., 2010), following the example of metropolitan regions.

Although some challenges are common to most scales (e.g., methodological process to develop indicators; accessibility, availability, condition, and reliability of data supporting the assessment; weighting methods), it is notable that different levels can also present different challenges (Verma and Raghubanshi, 2018). As with the regional scale, we can cite some obstacles: the selection of indicators, to truly represent the sustainability vision of the evaluated area; the unavailability of georeferenced data, which are appropriate to the assessment scale; and the publication of adequate results to guarantee the inclusion and participation of stakeholders, so that the evaluation is not only integrated, but effectively sustainable (Sala et al., 2015; Oliveira, Teixeira and Batalhão, 2022).

Some solutions to these and other challenges inherent in regionalized assessments have been debated by several researchers. An example is studies focused on the development of indicators that would enable interaction between local and regional scales and that advanced the debate on public participation in the evaluation process (Coelho et al., 2010). Other examples are works in which sustainability assessments were partially based (Graymore et al., 2009), or fully integrated (Boggia et al., 2018a), on tools aimed at spatial analysis (Geographic Information Systems - GIS), making use of georeferenced data, and the development of indexes based on remote sensing data (Vitor et al., 2020). These last examples converge with studies that indicate a trend in the use of GIS tools in SA (Olawumi and Chan, 2018) and new opportunities related to the use of indicators produced from data from Earth observation technologies (Ramos, 2019; Estoque, 2020).

However, there are still few works that attempt to overcome these challenges in an integrated way. That said, this study aims to broaden the discussion on the approach of SA on regional scales, proposing and applying a geospatialized performance assessment framework towards Sustainability. In the end, we generated an index that included different dimensions of the human-nature relationship, through the processing of georeferenced data.

This article proceeds in four sections: Section 2 describes the theoretical and methodological definition and construction stages of the proposed framework, in addition to a brief description of the case study region. Section 3 presents and discusses the results obtained from the previous steps, that is: selection and instrumentalization of indicators, weighing, aggregation, retroactive analysis, and sensitivity and, additionally, presents a complementary analysis relating the results obtained with socioeconomic indicators of the evaluated region. Section 4 explores the inferences that have been drawn from the discussion.

5.2 Materials and Methods

To achieve the objective of this work, we need to initially define the scope of the framework to be built. For this, we based on previous studies that sought to characterize and discover patterns and trends from the history of international scientific publications in the area of SA supported by tools for processing spatial data analysis (GIS). The different steps were defined, as well as the methods applied to construct the framework.

5.2.1 The scope of the framework

In general, the scope of a SA supported by GIS should be inserted in the context of Sustainability Science, that is, both the conceptual bases and the methodological guidelines that make up this framework should take care of a holistic approach, where the complex relationships between man and nature will be studied, in order to consider different multidimensional and spatial scales (Oliveira, et al., 2022).

Considering the theoretical outline raised by Oliveira et al. (2022), the scope of a geospatialized assessment should consider a confluent sustainability approach with that pointed out by the Global Agenda for Sustainable Development Goals (United Nations, 2015), that is, it is understood from an interpretation of the public policy approach and planning theory, to consider multidimensional integration. Regarding the methodological process, it is common for SA supported by GIS to use remote sensing tools and products, mainly to map land use and occupation. Furthermore, when dealing with decision problems where the spatial variable is indispensable, SA are usually integrated with multicriteria decision analysis (MCDA) techniques.

Because it is a framework aimed at evaluating on a regional scale, Oliveira et al. (2023), recommend that the process should allow communication between levels below and above the evaluated region, that is, in addition to being adaptable, the set of variables must be shareable between municipalities, but also between different regions. This characteristic still imputes to the framework a “What If” approach, that is, it enables the survey, or planning, of different scenarios, where new and/or existing policies and measures are evaluated based on scenarios relevant to different dimensions that involve the human-nature relationship (Salas, 2015).

That said, the scope of the framework proposed in this study will be to guide a multidimensional evaluation at the regional level, based on the goals defined in the 2030 Agenda (United Nations, 2015), and that generate spatialized results, in order to allow comparative analyzes. The results generated will aim to support decision-making and policy development, through the identification of priority areas through the measure of the region's performance in meeting Sustainable Development Goals (SDGs).

5.2.2 Steps and methods of framework construction

The framework construction process was developed from the definition of four steps and in each step a specific method was applied.

5.2.2.1 Selection of indicators

To feed the process of evaluating the performance of regions on the path of sustainability, we define the use of indicators that cross descriptively and methodologically with the goals defined in the 2030 Agenda. However, this global initiative establishes a total of 169 goals and a framework of 231 indicators for the 17 Sustainable Development Goals that involve various elements of the human-nature relationship, making the work of choosing the indicators to be used become a major challenge. Additionally, some aspects should be considered to define which indicators can or cannot be applied in a region.

Some authors indicate numerous adversities when defining sustainability indicators to be used ranging from conceptual challenges such as relevance to methodological challenges such as availability. Nevertheless, several authors recommend that the choice of SIs be made in order to allow the participation of the multiple actors involved (Ramos, 2009). Among other reasons, this participation is important so that the selected SIs are associated with the interpretation of sustainability given by the local community (Sala et al., 2015).

However, the framework proposed in this work does not aim to define a specific method of choosing indicators, but rather to point out paths that can help in an evaluation that allows measuring the performance of regions in meeting the SD Goals with the help of geospatialization. To do this, we defined the use of SIs that are in accordance with the goals set out in the 2030 Agenda, so that the SD, which seeks to evaluate, is understood from multidimensionality. Furthermore, data for an official framework of sustainability indicators are not yet available in Brazil at the regional level for the Sustainable Development Goals of the 2030 Agenda, which makes it very difficult to carry out regional assessment processes that contemplate, even partially, the internationally defined targets in each goal.

Thus, and observing the particularity of being a SA supported by GIS, we chose to select SI that have already been applied in SA that have used methods, tools or geospatialized data in different parts of the world, and that were validated by scientific methods in peer-reviewed articles and published in different specialized journals. In this sense, we conducted a search in the Scopus database with the terms “geographic information system”, “geographical information system”, “GIS”, “spatial data infrastructure”, “sustainability indicator”, “sustainable development” and “sustainability assessment”, which were considered only in documents classified as articles and reviews and comprising all the years of publication available in the Scopus database, that is, from 1990 to 2020. This search resulted in a total of 1721 documents.

Observing the scope defined for the proposed framework, we sought to identify articles that had effectively performed SA with multidimensional SI applications, in addition, we sought publications that met the condition of clearly presenting at least the identification of indicators, their methodological descriptions, as well as their units of measurement. To complete this stage, it was necessary to complete two moments. At first, we included in a database the content present in the titles, as well as in the summary and keywords of all 1721 documents, and a search of the terms "sustainability AND assessment" OR "sustainability AND assessing" OR "sustainability AND indicator" was performed, resulting in a total of 142 articles that, hypothetically, would have performed SA using SI. In the second moment, we did the detailed reading of these articles, and identified 13 (thirteen) documents that met the initial condition and that together provided a total of 308 indicators.

The last phase of the process of selecting the indicators consisted of identifying and excluding all indicators that presented methodological redundancies, that is, resulting in unique and distinct SIs, thus avoiding the use of identical, similar, or overlapping indicators. Thus, we conclude the identification and selection of a total of 230 unique indicators.

5.2.2.2 Identification of indicators aligned with 2030 Agenda targets

Several authors defend multidimensionality as a way of evaluating whether activities that involve the relationship between human and nature are favorable or not to sustainable development. This perception is directly related to the very interpretation of sustainability by those who evaluate it. Here, we propose a framework that has as a principle of sustainability interpreted by the approach of public policies and the theory of planning, that is, consider an integration between different dimensions (Patterson et al., 2017). Numerous studies guide basing this human-nature relationship from the three pillars of sustainability (Triple Bottom Line Approach – TBL), that is, by the social, environmental, and economic dimensions, while others add a fourth dimension, the institutional approach (Quadruple Bottom Line - QBL) approach.

However, when considering the use of the Agenda 2030 approach, it is necessary to understand that the SDGs may be related to more than one dimension at the same time, that is, there is no clear division of goals and, as a consequence of SDG indicators, among the social, environmental and economic dimensions (Tremblay et al., 2020). Thus, we chose to define different dimensions that more specifically reflect human activities and nature.

After separating the selected indicators into different dimensions, we carried out an identification work with the Targets and SD Goals. At this stage, we relate the methodological descriptions of the indicators contained in the publications with the conceptual descriptions of the goals contained in the 2030 Agenda. That is, we verified whether there was a coincidence of objectives between what was intended to be measured numerically in the indicators and what was intended to be achieved theoretically with the SDGs.

Therefore, all those that were not included in the scope of the global agenda were excluded, resulting in 90 indicators with characteristics similar to the global SDG indicators.

5.2.2.3 Instrumentalization of indicators with regional data

This stage consisted of identifying which SIs, among those selected in the previous stage, have data available regionally. To apply the proposed framework, we chose the Metropolitan Region of Goiânia as the study area. This area is located in the Brazilian Midwest region, more specifically in the State of Goiás, and occupies a total area of 7,397,203 km² with a composition of 21 municipalities, with Goiânia being the main city of the region, comprising 60% of the population of the metropolitan region (IBGE, 2021).

That said, free access databases were consulted for secondary data acquisition, making it possible to calculate the indicators according to the methodological description originally available in the articles where they were presented. In addition to the quantitative indicators that could be constructed through consultation in a statistical database, there was also a set of indicators that, for its conception, required the use of Remote Sensing products, as well as GIS tools. These indicators were operationalized through geographic data made available digitally by a collaborative network formed by nongovernmental organizations, universities and technology startup, called MapBiomas Brasil. The data used are derived from mapping land use throughout the Brazilian territory, through a pixel-by-pixel classification of Landsat satellite images of 30 meters, where forest areas, non-forest natural formations, agricultural use, non-vegetated areas, and bodies of water are pointed out.

At the end of the completion of all five stages, we obtained a total of 29 (twenty-nine) indicators, which will be called Regional Performance Indicators toward Sustainability (RPIS) from this stage, and which were previously scientifically validated, aligned with the goals of the 2030 Agenda, and divided into seven different dimensions.

5.2.2.4 Definition of the weighing, aggregation, and retroactive analysis process.

This stage is divided into two moments: 1-consists of defining the weights of the RPIS by the entropy method and; 2- in the aggregation of RPIS by the Spatial Sustainability Assessment Model (SSAM) and retroactive analysis process.

In the first moment, we carry out the weighing process, which in a multicriteria analysis is a crucial phase. Generally speaking, two are the possible approaches. The first one is the expression of the weights by experts or decision makers, who based it on their own experiences, knowledge and perception of the issue. Although the involvement of expert is usually considered as the preferred scenario, in some contexts the use of this approach can be problematic. In complex scenarios, the user-defined subjective weighing method can be too difficult to apply and may lead to unsatisfactory results because the decision-maker(s) and/or experts may be unable or unwilling to provide cohesive and exact numerical judgments regarding the relative importance or weights of criteria (Boroushaki, 2017; Rocchi et al., 2022).

These problems can be overcome by using an objective weighing process, which is carried out independently from the subjective preferences of experts. The available methods are several including statistical approaches (Zardari et al., 2015). In this study we applied an entropy-based object weighing scheme. The weights for the set of criteria are quantified using the Shannon's entropy theory (Shannon, 1948) of the information. Information entropy is a measure of the degree of disorder within a system. It can quantify the amount of expected and useful information content within criterion values, and it measures the contrast intensity among a set of criteria within a decision matrix (Boroushaki, 2017). Based on Shannon's entropy concept, the entropy index, E_i, for the *i-th* criterion can be calculated as follows:

$$E_i = \begin{cases} -\frac{\sum_{i=1}^{m} nij \ln(nij)}{\ln(m)} \end{cases} \tag{1}$$

When $p_{ij}= 0$ also $E_i= 0$.

E_i is always in the interval 0-1. The value $1 — E_i$ describes the degree of diversity for the *i-th* criterion. Using the degree of diversity, entropy-based weights for each criterion, W_j, can be calculated as:

$$w_i = \frac{1 - E_j}{\sum_{i=1}^{m}(1 - E_j)} \tag{2}$$

In the second moment, we carried out the aggregation of SI by spatial sustainability assessment model (SSAM) and back analysis. SSAM is a powerful tool initially created in 2007 under the name UmbriaSUIT 1.0, and was developed with the efforts of researchers from the Università degli Studi di Perugia-IT in collaboration with ARPA (Regional Environmental Protection Agency of Umbria-Italy). It was a tool developed with the objective of comparing the sustainability of different territorial areas, and can be applied at different scales, using multiple criteria, and obtaining a sustainability index from environmental and social and economic indicators. This tool went through two update periods, one in 2014 and another in 2021 (Boggia et al., 2018; Rocchi et al., 2022).

In general, the tool development steps include a ranking of alternatives (evaluation units) through an MCDA model and the extraction of rules for the retroactive analysis process.

The multicriteria algorithm used in SSAM is the TOPSIS (Technique for Order Preference by Similarity to Ideal Design) which generally defines a ranking based on the distance of the worst alternative and the proximity of the best, represented by the lowest and highest value of each indicator, respectively, or vice versa, depending on whether it is an indicator to be maximized or minimized (Hwang and Yoon, 1981). Thus, the indicators representing each of the three dimensions can be treated individually, resulting in three distinct indices, for each geographic unit analyzed, i.e., environmental index, economic index and social index. Optionally, one can also weight (or not) the values of the three previous indices resulting in an aggregated global sustainability index (Boggia et al., 2018). After the aggregation process, the results are presented for reading and interpretation, either in the alphanumeric format, or in the graphic format (maps, cartograms and graphs). This graphical output in the form of maps illustrates the results of the multicriteria analysis for each feature that makes up the studied region, through a coroplethic map, where the different colors represent the level of sustainability (Boggia et al., 2018; Rocchi et al., 2022).

Another important analysis that can be performed with SSAM is the extraction of decision rules that aim to explain the positions obtained by analysed alternatives (in the case of the present study, each municipality) in the ranking, based on the criteria that were used, thus increasing the ability of retroactive analysis. However, this type of analysis is possible only for the global index (Boggia et al., 2018).

In comparison to the previous version, SSAM expands the possibility of sustainability assessments with regard to the number of dimensions to be considered, bringing greater flexibility in their use. If previously there was a limitation by the three pillars of sustainability (environmental, social and economic), they can now be added or replaced by custom dimensions. Another important change to highlight is the type of vector file that is supported. Until the previous version, the plugin used geographic vectors in shapefile format, from the current version, starts to use the geopackage format (Rocchi et al., 2022).

5.3 Results and Discussion

5.3.1 The challenges in the selection and instrumentalization of indicators in the context of the 2030 Agenda

From the structured search in the Scopus database, 1721 articles related to sustainability assessment processes and GIS tools were identified. The method of selecting indicators sought, from then on, to find articles that clearly declared which ones were used in SA and that indicated their descriptions so that they could be replicated, resulting in a number of 13 publications that meet these specifications (step 1 of the construction of the framework). This low number of articles (less than 1%) can be explained due to the indiscriminate use of the term "sustainability" and "sustainability assessment". Alfredo et al. (2018) draw attention to the fact that these terms have been used without a clear criterion about what type of sustainability approach is treated in the evaluation process. Numerous studies present only biophysical indicators for soil mapping (Faichia et al., 2020) or water resources (Shehata and Mizunaga, 2019), in addition to land use, in which sustainability was related only to the percentage in which natural vegetation occupies or does not the evaluated area.

On the other hand, despite the low number of articles, 308 indicators were identified, representing an average of more than 23 indicators per publication. Table 5.1 lists the publications and the number of indicators found in each one.

Table 5.1 Reference of publications that contributed to the selection of indicators.

References	**n. of indicators**
Lautso, K.; Toivanen, S. SPARTACUS system for analyzing urban sustainability. Transp. Res. Rec. 1999, 35–46.	23
Liu, L. Urban environmental performance in China: A sustainability divide? Sustain. Dev. 2009, 17, 1–18.	22
Graymore, M.L.M.; Wallis, A.M.; Richards, A.J. An Index of Regional Sustainability: A GIS-based multiple criteria analysis decision support system for progressing sustainability. Ecol. Complex. 2009, 6, 453–462.	13
Zhang, H.; Uwasu, M.; Hara, K.; Yabar, H. Sustainable urban development and land use change-A case study of the Yangtze River Delta in China. Sustainability 2011, 3, 1074–1089.	8
Xu, Z.; Coors, V. Combining system dynamics model, GIS and 3D visualization in sustainability assessment of urban residential development. Build. Environ. 2012, 47, 272–287.	20
Shen, L.; Kyllo, J.M.; Guo, X. An integrated model based on a hierarchical indices system for monitoring and evaluating urban sustainability. Sustain. 2013, 5, 524–559.	20
Salvati, L.; Carlucci, M. A composite index of sustainable development at the local scale: Italy as a case study. Ecol. Indic. 2014, 43, 162–171.	58
Wang, Q.; Tang, S.; Hu, J.; Chen, X.; Wang, L. Performance measurement system for assessing transportation sustainability and community livability. Transp. Res. Rec. 2015, 2531, 113–120.	13
Alshuwaikhat, H.M.H.M.; Aina, Y.A.Y.A. GIS-based urban sustainability assessment: The case of Dammam City, Saudi Arabia. Local Environ. 2006, 11, 141–161.	35
Lu, C.; Wang, C.; Zhu, W.; Li, H.; Li, Y.; Lu, C. GIS-based synthetic measurement of sustainable development in loess plateau ecologically fragile area-case of qingyang, China. Sustain. 2015, 7, 1576–1594.	38
Lu, C.; Xue, B.; Lu, C.; Wang, T.; Jiang, L.; Zhang, Z.; Ren, W. Sustainability investigation of resource-based cities in northeastern China. Sustain. 2016, 8	22
Boggia, A.; Massei, G.; Pace, E.; Rocchi, L.; Paolotti, L.; Attard, M. Spatial multicriteria analysis for sustainability assessment: A new model for decision making. Land use policy 2018, 71, 281–292.	18

Paolotti, L.; Del Campo Gomis, F.J.; Agullo Torres, A.M.; Massei, G.; Boggia, A. Territorial sustainability evaluation for policy management: The case study of Italy and Spain. Environ. Sci. Policy 2019, 92, 207–219.	18

If we look at the publication dates of the selected articles, we can see that approximately half were published between 2015 and 2020. This finding may be directly related to the participation of the scientific community in the premises set out in the 2030 Agenda, which, despite officially adopting a global SD Indicators officially from July 2017, already pointed out possible ways for nations to seek sustainability from the goals set in 2015. Therefore, this may have influenced more studies to deal with sustainability assessments in order to integrate different dimensions. However, in this study, we identified that, although the publications provide a large number of different multidimensional indicators, and with different objectives, there may be similarities between nomenclatures and construction methods.

Thus, part of the indicators found in the articles presented identical methodological descriptions, that is, its definition is exactly the same in two or more published papers, such as the case of the indicator "Number of crimes per 1000 inhabitants", identified as belonging to the dimension "Quality of life" by Salvati and Carlucci (2014) and the indicator "Comfort Index 1" described as "Crime rate (crimes/1000 population)" by Shen et al. (2013). In other cases, the indicators contained methodological coincidences or presented characteristics that were identified as overlapping. To exemplify the latter, we mention the indicator "Per capita education and health spending" (Liu 2009) and "Education Spending" (Lu et al. 2016). In the first, the values referenced comprised expenditures on education and health, simultaneously, in urbanized areas of some Chinese regions, while the second refers to education spending only in cities in north-eastern China. Although different, they are considered overlapping because they used similar data in their composition. Therefore, after rigorous filtering, we selected a total of 230 unique and distinct indicators.

The results of steps 2 and 3 were obtained from the separation of unique indicators into different thematic axes. This organization in dimensions made it easier to identify indicators that present confluent descriptions with what advocates the objectives and SDG targets of the 2030 Agenda, and consequently with the global SDG indicators. In total, 7 (seven) dimensions were defined, namely: Education, Employment, Environment, Equality, Health, Service, and Well-being. We also add that the dimensions defined are a result of adaptations of works such as Lautso and Toivanen (1999), Salvati and Carlucci (2014), Lu et al. (2015), and Rocchi et al.

(2022). At the end of this process, a total of 90 unique indicators were identified, distinct from each other, and associated with the SD Goals.

Therefore, only approximately 40% of the total of individual indicators agrees with the principles of the 2030 Agenda. Such an occurrence does not necessarily mean that the SAs present in the articles disagree with the principle of sustainability adopted in this study, since some indicators may be closely associated with the way in which the agents involved in the process interpret sustainability and the relevance that the criteria have regionally and locally. To illustrate this particularity, we mention the indicator "Pine plantations" applied in a SA by Graymore (2009) in which the planted area of pine trees could indicate greater or lesser degree of sustainability in the environmental dimension of a region of Australia. Another example is the indicator "Pedestrianization" (Habib, 2006), which aimed to identify the distance travelled on foot or by bicycle by urban residents of the city of Dammam, Saudi Arabia, as a criterion of the social dimension. Therefore, despite the multidimensional approach, these are indicators with characteristics inherent to the evaluated regions.

Step 4 consisted of identifying, among all indicators associated with the SDG targets, those that could be applied to the Metropolitan Region of Goiânia. The search in official databases resulted in 29 RPIS. Table 5.2 shows the sources consulted, as well as the number of indicators that were made possible from the available data for the evaluated region.

Table 5.2 Sources consulted to collect secondary data.

Source	**N. of RPIS**
IBGE - Brazilian Institute of Geography and Statistics	11
MapBiomas Brasil - Collection 5	05
IMB - Mauro Borges Institute for Statistics and Socioeconomic Studies	04
IPEA - Institute of Applied Economic Research	03
SNIS - National Sanitation Information System	02
MPT - Public Ministry of Labor	01
INEP - National Institute of Educational Studies and Research Anísio Teixeira	01
AtlasBrasil - Atlas of Human Development in Brazil	01
SIOPS - Public Health Budget Information System	01

In the current study, some challenges were identified when instrumentalizing indicators associated with the SD Goals for the evaluated region. Among all the challenges, the unavailability and non-disaggregation of secondary data were the main obstacles. This is because when querying the existing statistical databases, sometimes there was no data referring to a given indicator due to the degree of complexity of its construction, for example, the indicator "Degree of broadband diffusion in business" or the lack of data separated by regions or municipalities, such as the indicator "air quality ". It should also be noted that our area of study is composed of small municipalities with low representativeness at the state and national levels, making it even more difficult to have data that would enable the instrumentalization of some indicators. That is, even if it was possible to find data from a specific indicator for larger municipalities, such as for the state capital Goiânia, this was not the case of economically inexpressive municipalities as the case of Caturaí, and this makes it impossible to analyze the region as a whole. Therefore, only criteria that were available for all the municipalities that make up the region were considered.

Another important adversity for the construction of the indicators was the non-temporal uniformity of the data. For municipalities, we found the same indicators, but at different times. Thus, we would have the same criterion based on different moments, making its use unfeasible. In addition, for the survey of a scenario based on the indicators used, it is necessary that they be referred to the same temporal moment. However, when consulting the statistical database, we found data that referenced to different dates, with differences of eight years or more, so we obtained indicators for the same region, but with different periods. In the impossibility of using indicators with the same reference date, we chose to use the closest possible date.

In addition to what has already been mentioned, the reliability and discrepancy between similar data, but on different bases, were configured as a difficulty found in the instrumentalization of SDG indicators. The lack of metadata of the data used makes different results can be found, in different sources, for the same indicator. In this case, we chose to use those that are made available by sources with the highest number of available data.

The identification of each RPIS instrumented for the evaluated region, as well as the way in which they are distributed in different dimensions, the SD targets to which they are related, and their respective methodological descriptions are described in Table 5.7 (supplementary material). In addition, we built an infographic (Figure 5.1) in which you can verify punctually the objectives and SD targets in which each dimension is related and how many indicators are inserted in each dimension after the definition of the criteria to be applied.

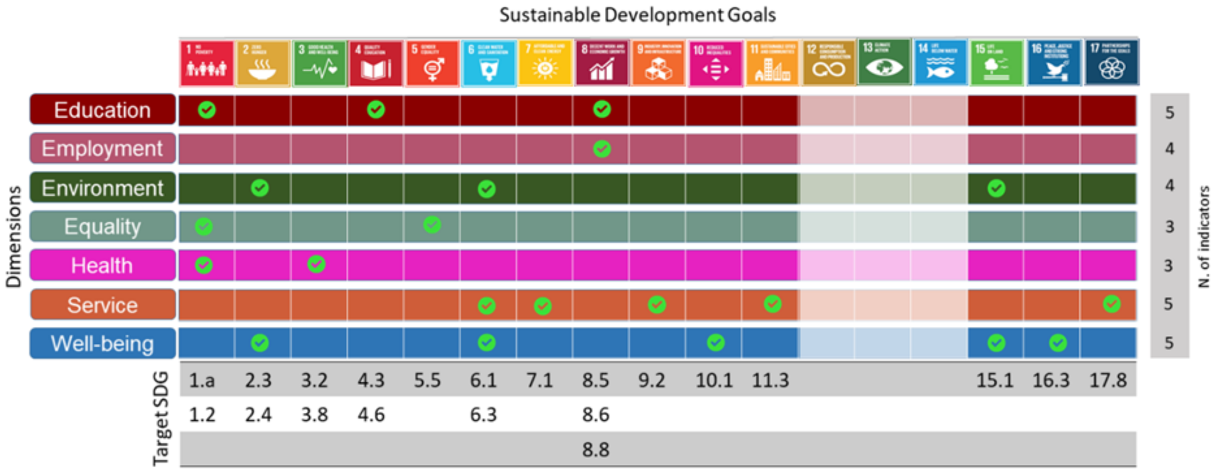

Figure 5.1 SD Goals, targets and dimensions contemplated.

Among the seven defined dimensions, "Education", “Service”, and "Well-being" are those that have the highest number of indicators (5) and are also among the dimensions that relate to the largest number of SDGs. On the other hand, if we observe from the point of view of the distribution of objectives, we realize that they are mostly associated with only one or two dimensions. This indicates that the use of a larger number of dimensions that go beyond the social, environmental, and economic pillars, can help in the interpretation of the results to the extent that it seeks to understand not only how the evaluated region is in meeting the SDG targets, but also which themes involving society and the environment need greater attention by decision makers.

In this particular case, the absence of indicators in SDGs 12,13 and 14 is perceived, and it is mainly due to two key factors. First, because it is a SA at the regional level, it is necessary to understand the geographical particularities of the evaluated area. The Metropolitan Region of Goiânia is located in the center of Brazil, with no direct relationship with oceans, seas, or marine resources, so it is no possibility of considering goals related to SDG14 (Life in Water). Second, it is justified from the method of choosing criteria adopted in this article, that is, no selected article had unique indicators related to SDG12 (Responsible Consumption and Production) and SDG 13 (Action against global climate change). However, the latter do not have restrictions regarding application in Brazilian regions.

5.3.2 Weighing, spatialized index generation and back analysis

5.3.2.1 Weighing

The weights calculated with the Entropy method are reported in the Table 5.3. Each dimension has been considered as separated and the weights sum to 1 within it. The weights for the aggregation of the different dimensions is based on the mean weights, calculated as follow:

$$w_d = \frac{1}{n_d} * 100 \qquad (3)$$

Where w_d is the mean weight of each dimension, n_d is the number of dimensions (6 in this paper) and 100 is a factor for reporting the weight in the scale 1-100 which is the one used in SSAM for aggregating dimensions.

Table 5.3 Weights

Criteria	Sustainability dimensions	Criteria Weights	Dimensions weights
G1_So_Education Spending	Education	0.200229	14.29
G4_So_Illiterate population	Education	0.19997	
G4_So_Population with tertiary-level education	Education	0.19738	
G4_So_The number of students enrolled	Education	0.201366	
G8_So_Drop out of school	Education	0.201056	
G8_So_Work Related Accidents	Employment	0.259618	14.29
G8_Ec_Density of workers	Employment	0.210757	
G8_Ec_Unemployment Rate	Employment	0.264112	
G8_Ec_Jobs/housing balance	Employment	0.265513	
G2_En_The fertilizing intensity of chemical fertilizer	Environment	0.274939	14.29
G6_En_Domestic water consumption	Environment	0.19036	
G15_En_Per capita forest land area	Environment	0.259668	
G15_En_Green coverage ratio	Environment	0.275033	
G1_Ec_People at Risk of Poverty	Equality	0.330853	
G5_Ec_Female workers to total workers	Equality	0.334598	14.29
G5_Ec_Female participation rate	Equality	0.334549	
G3_So_Age standardized Mortality rate - up to five years	Health	0.33448	14.29
G3_So_Human health	Health	0.334599	
G1_Ec_per capita health spending	Health	0.330921	
G7_So_Per capita electricy consumption	Service	0.207857	14.29
G17_So_Persons per internet subscriber	Service	0.207823	
G9_Ec_Working in manufacturing industry	Service	0.206931	
G6_En_Water consumption	Service	0.208747	

G11_En_Artificial Surface Area	Service	0.168642	
G2_So_Per capita net income of farmers	Well-being	0.169658	14.29
G6_So_Water density (water area/total)	Well-being	0.20165	
G16_So_Crime rate	Well-being	0.216674	
G10_Ec_Household Disposable Income	Well-being	0.216352	
G15_En_Green space index	Well-being	0.195665	

5.3.2.2 Aggregation

From the defined weights, the process of aggregation of indicators into spatialized indexes was carried out using SSAM, and the results are presented in the form of choropleths maps (areas symbolized with colors) (Figure 5.2).

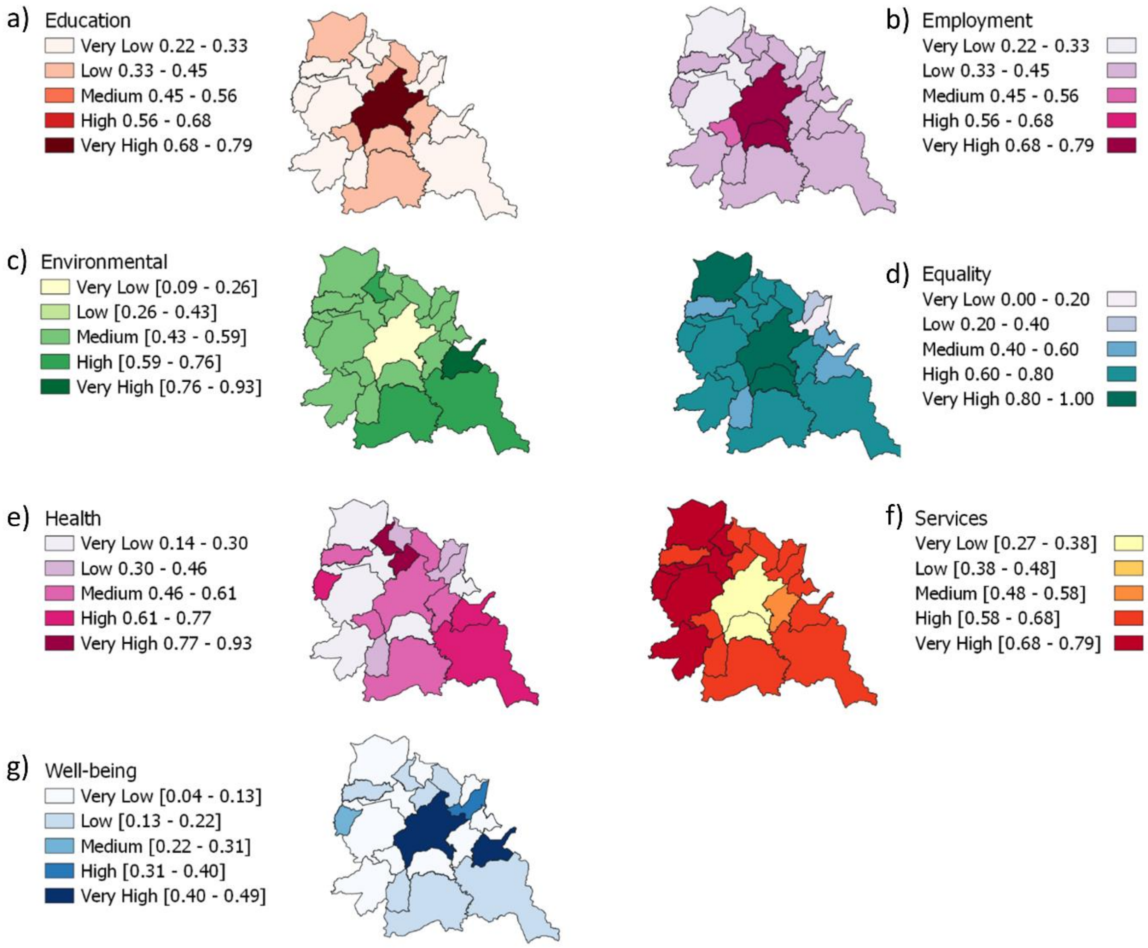

Figure 5.2 Maps of the seven dimensions: a) Education Index, b) Employment Index, c) Environmental Index, d) Equality Index, e) Health Index, f) Services Index and g) Well-being Index.

From the defined weights, the process of aggregation of indicators into spatialized indexes was carried out, and the results are presented in the form of choropleths maps (areas symbolized with colors) where they were separated by performance in the fulfilment of the SDGs in each dimension, categorized into five classes, namely: very low, low, medium, high, and very high.

The results indicate that the Service dimension is the one with the highest number of municipalities (06) with optimal ranking, that is, Very High. In contrast, five dimensions (out of a total of seven) have only two or fewer municipalities in the highest class. If we analyze the other extreme of the classification, we see that the Education dimension is the one with the highest number of municipalities (12) with the worst classification, that is, Very Low. However, the Environmental, Equality, and Services dimensions have only two or fewer municipalities in the lowest class.

Optionally, the SSAM tool also provides an overall rating through the weighted sum. In this work, we name it General Performance Index towards Sustainability (GPIS). Therefore, we noticed that only one third of the municipalities achieved a GPIS classified as High or Very High, while more than half are classified as Low or Very Low. This low ranking of most municipalities is mainly due to the dimensions of Education, Employment, and Well-being.

More specifically, we observe the municipalities of Goiânia, Santo Antônio de Goiás and Caldazinha classified as class 1 (Very High). Then we see Brazabrantes, Hidrolândia, Santa Bárbara de Goiás and Abadia de Goiás in class 2 (High), Bela Vista de Goiás, Nerópolis and Senador Canedo in class 3 (Medium), Nova Veneza, Inhumas, Caturaí, Guapó, Aragoiânia, Aparecida de Goiânia and Goianira in class 3 (Low) and Trindade, Terezópolis de Goiás, Bonfinópolis and Goianápolis in class 4 (Very Low).

In Figure 5.3, the GPIS is geographically distributed, facilitating a performance comparison analysis between the cities that make up the metropolitan region. When we look at the map, we do not perceive a spatial pattern for the general classification of municipalities, as is the case in Paolotti et al. (2019) and Boggia et al. (2018b). However, we can see spots that indicate a greater concentration of poorly ranked municipalities to the north (low) and west (very low) of the evaluated region, whereas municipalities in the highest classes are concentrated in greater numbers in the centre (very high). That is, this spatial format of presentation of the results can provide the analyst with the geographical identification of priority areas that need more attention in the definition of public policies.

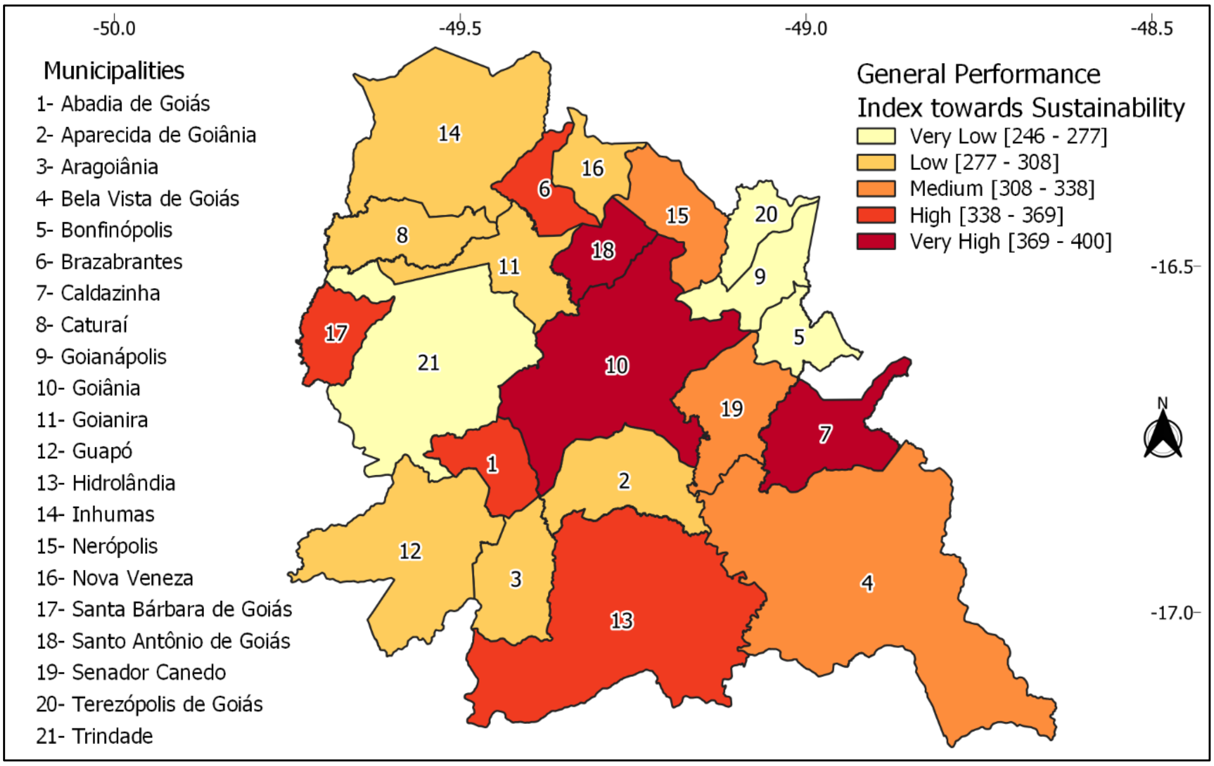

Figure 5.3 General Performance Index towards Sustainability, by municipality of the Metropolitan Region of Goiânia.

5.3.2.3 Back analysis

The SSAM tool still allows for a retroactive analysis that helps to obtain a more detailed understanding of the final result, as it allows the evaluator to observe which indicators influence the final result the most. Therefore, in addition to ensuring greater transparency in the evaluation, retroactive analysis allows the identified indicators to be responsible for the final classification of municipalities. For example, we selected some results of back analysis (Table 5.4). The first column describes the rule where it spells out the threshold values that cause a specific indicator to determine the position of the municipality in a given class. The second, third, and fourth columns of the table detail what the indicators, values, and class are, respectively. The fifth column indicates which municipalities the rule is true for.

In the case of the application of the framework in the Metropolitan Region of Goiânia, retroactive analysis makes us understand that the low performance in the "Working in Manufacturing Industry" indicator in the dimension "Services" was determinant for the municipality of Bonfinópolis to be included in the Very Low class. If we consider the same dimension, the high performance in relation to the indicator "Persons per Internet Subscriber" is determinant for the municipality of Goiânia to be classified as Very High.

Table 5.4 Back analysis: some examples

Rule	Indicator	Value	Class	Counties
IF [(9_SER_WMI <= 9.3)] THEN AT MOST CLASS "very low"	Working in manufacturing industry	<=9,3	Very Low	Bonfinópolis, Nerópolis
IF [(3_HLT_HH <= 0.81)] THEN AT MOST CLASS "low"	Human health	<=0,81	Low	Senador Canedo Caldazinha
IF [(8_EMP_WRA <= 1.65)] THEN AT LEAST CLASS "high"	Work Related Accidents	<=1,65	High	Caturaí
IF [(17_SER_PIS >= 6.87)] THEN AT LEAST CLASS "very high"	Persons per internet subscriber	>=6,87	Very High	Goiânia

5.3.2.4 Sensitivity

Sensitivity analysis aims to verify the stability of the outcomes, and therefore of the model, checking the extent of variation in the output when parameters are systematically varied over a given range of interest, either individually or combined (Delgado and Sendra, 2004). In spatial SA is very common to carry out sensitivity analysis on weights, changing them or performing the weights stability analysis (Delgado and Sendra, 2004). However, in case of TOPSIS application this approach seems less effective because the method is subject to rank reversal, which is a phenomenon also present also in other multicriteria methods (i.e., the Analytic Hierarchy Process (AHP)) (Rocchi et al. 2022). A rank reversal happens when the alternatives' order of preference changes by adding or removing alternatives from the decision problem (Garcia and Lamata, 2012). The presence of rank reversal is considered a serious issue, as it is a violation of the invariance principle of utility theory (Wang and Lou, 2009).

To understand if there is the risk of rank reversal for the current application, a sensitivity analysis has been performed using the approach suggested by García and Lamata (2012), adding two fictitious alternatives which correspond with the best possible valuation and with the worst possible one and running again the model. Moreover, since SSAM group the different results in classes, we focused our attention on switch between them. Table 5.5 reports the results of such analysis.

Table 5.5 Sensitivity analysis: results

	Original classification	After sens. An.	Behaviour
Goiânia	Very high	Very high	Stable
Caldazinha	Very high	High	Worsen
Brazabrantes	High	High	Stable

Santo Antônio de Goiás	Very high	High	Worsen
Santa Barbara de Goiás	High	High	Stable
Hidrolândia	High	Medium	Worsen
Abadia de Goiás	High	Medium	Worsen
Bela Vista de Goiás	Medium	Medium	Stable
Nerópolis	Medium	Medium	Stable
Inhumas	Low	Low	Stable
Caturaí	Low	Low	Stable
Senador Canedo	Medium	Low	Worsen
Nova Veneza	Low	Low	Stable
Guapó	Low	Low	Stable
Aragoiânia	Low	Very low	Worsen
Goianápolis	Very low	Very low	Stable
Terezópolis de Goiás	Very low	Very low	Stable
Goianira	Low	Very low	Worsen
Aparecida de Goiânia	Low	Very low	Worsen
Trindade	Very low	Very low	Stable
Bonfinópolis	Very low	Very low	Stable

The most interesting results of the sensitivity analysis is that none of the regions improved its position: they kept or worsen their class. In particular, the class Very high after the analysis is limit to one region, Goiânia, which score always as the absolute best, while the Very low class almost double its size at the expense of the Low class. Class High is stable as number of regions involved, however only two remained stable; the Medium class is now made by four, but only Bela Vista de Goiás and Nerópolis are stable. Sensitivity analysis on the classes do not evidence true cases of rank reverse (i.e., switching position) but more a general worsen of the results.

5.3.3 Complementary analysis for the GPIS used for the Metropolitan Region of Goiânia.

5.3.3.1 A parallel between performance towards sustainability and GDP.

We chose to carry out an additional analysis relating GPIS and GDP, following the example of Rocchi et al. (2022). We can state, according to the result obtained and shown in Figure 5.4 (scatter chart), that there is a weak relationship between the two variables (R2 0.3032). That is, approximately 70% of the municipalities do not have GPIS values explained by the value achieved by GDP.

To deepen this analysis, we will cite some municipalities as an example to relate the results obtained by sustainability performance and the GDP value for the year 2010. This time frame coincides, for the most part, with the dates of the data that made up the indicators used.

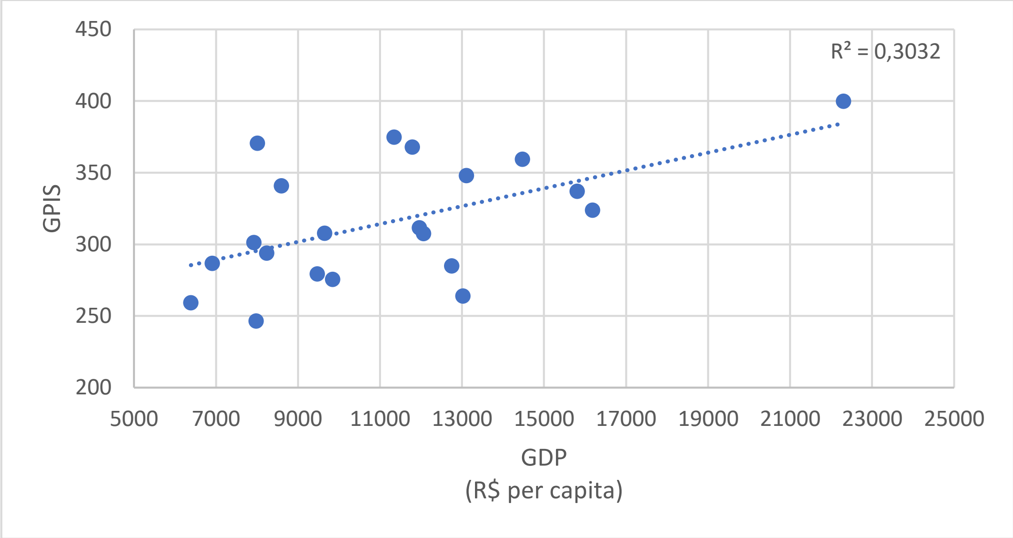

Figure 5.4 Scatter plot: Gross domestic product (Reais per capita) and General Performance Index towards Sustainability

Among the municipalities that are in the Very High class, we can observe Goiânia, capital of the State of Goiás, the city with the largest number of inhabitants and the highest GDP in the evaluated region. Although ranked in the low class of the Environmental dimension and in the medium class in the Health dimension, the municipality reaches the highest classes in four dimensions (Education, Employment, Equality, and Well-being). Therefore, on the one hand, this result can be explained by the large number of higher education and job vacancies offered in the municipality, which historically has had people migrating from smaller cities to qualify professionally in the capital. On the other hand, it has a high rate of occupation of its territory with urbanized areas, leaving few areas with the remaining natural vegetation cover.

However, other municipalities with high GDP did not result in a good ranking in the GPIS. This is the case of Aparecida de Goiânia, which had the third largest GDP in the State, and which appears in the low or very low classes in five out of seven dimensions (Environmental, Education, Health, Services, Well-Being), and in the highest class only in Employment and Equality. Another example is the municipality of Senador Canedo (6th largest GDP in the State of Goiás), which appears in the global sustainability index in the median position. This result reflects what was achieved in the Health, Services, Equality, and Employment dimensions, all in the Medium class, while the other classes scored in the low or Very Low classes.

In the same sense, two other results corroborate the evidence that GDP has little influence on the final result. We verified that Caldazinha municipality, which in 2010 had only the 178th GDP in the State of Goiás (out of a total of 246 existing municipalities), is ranked in high or very high classes in the dimensions of Health, Services, Environment, and Wellbeing. Furthermore, the municipality of Santo Antônio de Goiás (the 169th GDP in the state), which achieves good results in the dimensions of Health, Equality, and Service. Both were ranked in the highest class of the GPIS.

5.3.3.2 Performance towards sustainability and socioeconomic performance: similarities, differences, and their reflection.

The Goiás government, the state in which the Metropolitan Region of Goiânia is located, generates an index every two years for all its municipalities, called the Municipal Performance Index (MPI). This index aims to support planning, in addition to evaluating the results of government actions over time. For this, the MPI uses 34 quantitative variables representing six dimensions (or areas), namely: Economy, Employment, Infrastructure, Health, Education, and Public Security. This index allows the government to perform a socioeconomic diagnosis of municipalities, in addition to comparing the performance achieved between them (IMB, 2013).

Unlike from the GPIS, the MPI does not intend to be characterized as an index that indicates the proximity (or distance) of municipalities towards sustainability (IMB, 2013). This is clear in that it does not address, for example, variables related to environmental issues or gender equality. However, there is a similarity between some dimensions that the two indices are intended to assess. Three of the six dimensions of the MPI are directly related to the GPIS (Education, Employment, and Health), as well as conceptual coincidences between some variables such as Crime Rate and Per Capita Electric Energy Consumption, which bring other dimensions together despite different nomenclatures (e.g., infrastructure, public security).

Thus, it is normal to expect some communication between the results obtained in both indexes, even with different objectives. This time, we decided to perform an analysis of the relationship (Figure 5.5) between MPI results for 2010 and the results achieved by municipalities in the GPIS.

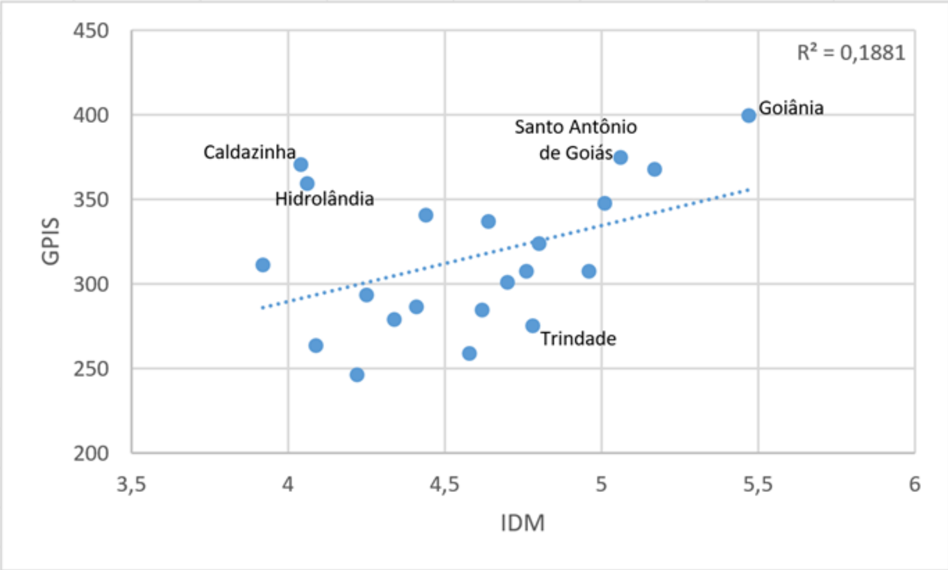

Figure 5.5 Scatter plot: Municipal Performance Index and General Performance Index towards Sustainability.

The results found from the scatterplot indicate that the relationship between the two indices is even weaker (R2 0.1881) compared to GDP (Section 5.3.3.1). This result can have two main explanations: (1) although the GPIS considers equal weights between the different dimensions, there is a difference in weights between the indices used, while the MPI considers equal weights both between dimensions and between the variables used; and (2) despite some similarities, the fact that the GPIS encompasses some dimensions that are ignored in the MPI (i.e., Environmental, Equity, and Well-being) can directly influence the performance results of municipalities. To better understand this relationship between the performance index towards sustainability and the socioeconomic performance index, we will use the ranking of some emblematic municipalities as an example, considering only the spatial area of the metropolitan region.

The municipality of Goiânia was in the highest position in both indexes. This indicates that the capital is distinctive in several regions, not only in the metropolitan area, but throughout the State of Goiás. The second best placed in the GPIS is Santo Antônio de Goiás, which reaches the third place in the MPI, that is, it obtained a similar performance in both indexes. However, if we look at Caldazinha, which has the third position in the GPIS, it is only the twentieth position (out of 21) in the MPI. More specifically, when looking at the dimensions separately, it is precisely in Environmental and Well-Being that Caldazinha has its best results, dimensions that are little or not addressed by the existing socioeconomic performance index.

Similar situations of discrepancy in the ranking occur with the municipalities Hidrolândia (5th GPIS/19th MPI) and Trindade (18th GPIS/7th MPI).

5.4 Conclusion

The present study designs an evaluation process in which GIS techniques and tools are designed with the aim of indicating and communicating the performance of different regions toward sustainability. The application of the proposed framework demonstrated that its theoretical and methodological design is comprehensive in terms of human-nature relationships, it is flexible in terms of criteria and their temporalities, it is transparent in terms of the methods and mathematical models used, and democratic in terms of communication of results.

The theoretical approximation of the framework with the goals and objectives of the 2030 Agenda, and consequently the multidimensional approach, allowed the use of indicators that extend to several and different aspects that translate society's activities and its interaction with nature. In addition to this holistic perspective, the framework allowed for a unitary analysis of the region based on the integration of dimensions.

The process of selecting and instrumentalizing indicators was shown to be efficient, as it is fully adjustable. Two important features should be highlighted: (1) a regionalized assessment may require the use of common variables across municipalities, which makes intraregional comparisons possible, or common variables across different regions, allowing for interregional comparison, and the present framework allows the insertion or exclusion of indicators, as well as the increase or reduction of the variables used; (2) the use of GIS-derived tools or products makes it possible to obtain data from different moments, either to assess the effectiveness of public policies already implemented or to assess the effect of new measures.

The framework presents a simple and clear proposal regarding mathematical processes. In particular, the weighing proposal, which can be changed or adapted based on the understanding of the people involved, after all, the importance given to one or another dimension (or indicator) may vary between different regions.

Whether related to each dimension separately, or in relation to the general index, the communication of results in the form of color maps makes it possible to take the understanding of the stage of performance towards sustainability of society as a whole, that is, beyond specialists and managers, facilitating the participation of the civil community in future measures and public policies.

5.5 Study Limitations/Strengths

Despite the proposed framework presenting flexibility and scope in the choice of variables, in the application presented, there was no participation of stakeholders in the process of selection and weighing of indicators, which can lead to results that do not translate, more reliably, the interpretation of sustained sustainability by the population that lives there.

In addition, the proposal presented indicates a possible path to be considered for future research on the topic of regional sustainability, and the opportunities for using GIS resources at different stages of the evaluation process.

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5.7 Supplementary material

Table 5.6 Methodological information for each indicator.

Indicator	Dimension	SD Target	Methodological Description	Year	Weight	Gain/Cost	Unit of Measure
Education Spending	Education	1.a	Education spending per capita	2014	0,200228592	gain	$ per capita
Illiterate population	Education	4.6	Percentage of population aged 15 years and over who can both read and write with understanding a short simple statement on his/her everyday life. Generally, 'literacy' also encompasses 'numeracy', the ability to make simple arithmetic calculations. Adult illiteracy is defined as the percentage of the population aged 15 years and over who cannot both read and write with understanding a short simple statement on his/her everyday life	2010	0,199969855	cost	% of population
Population with tertiary-level education	Education	4.3	Population with higher education	2010	0,19737977	gain	% of population
The number of students enrolled	Education	4.6	Number of students enrolled	2010	0,201365585	gain	every 10.000 people
Drop out of school	Education	8.6	Represents the rate of young people who leave their studies prematurely	2010	0,201056199	cost	% of young people who leave their studies prematurely
Work Related Accidents	Employment	8.8	Work accidents.	2010	0,259618431	cost	per 1.000 occupied
Density of workers	Employment	8.5	Calculated by dividing the economically active population by the area of the municipality in km2	2010	0,210756581	gain	Workers by km2
Unemployment Rate	Employment	8.5	Persons aged 15 and over unemployed in the reference week/Persons aged 15 and over in the workforce in the reference week) X 100	2010	0,264112189	cost	% of Persons aged 15 and over in the workforce

Jobs/housing balance	Employment	8.5	The balance of jobs and housing is the ratio of jobs to housing in a municipality	2010	0,265512799	gain	per house
The fertilizing intensity of chemical fertilizer	Environment	2.4	Percentage of agricultural establishments that use fertilization	2017	0,274938904	cost	% of agricultural establishments
Domestic water consumption	Environment	6,1	Consumed per household 1,000 m³/year	2018	0,190360469	cost	1.000 m3 per year
Per capita forest land area	Environment	15.1	Result of dividing the forest area by the number of inhabitants	2010	0,259667757	gain	m2 per capita
Green coverage ratio	Environment	15.1	Forest percentage in relation to the total area of the county	2010	0,27503287	gain	% of total area of the county
People at Risk of Poverty	Equality	1.2	Population below the poverty line	2010	0,330853009	cost	% population
Female workers to total workers	Equality	5.5	Calculated the percentage of the number of economically active women in relation to the total number of economically active people	2010	0,3345984	gain	% of total number of economically active people
Female participation rate	Equality	5.5	Calculated by dividing the total number of employed women by the total number of employed persons	2010	0,334548591	gain	% of total number of employed persons
Age standardized Mortality rate - up to five years	Health	3.2	Mortality up to five years of age	2010	0,334480101	cost	deaths/1.000
Human health	Health	3.8	The Longevity dimension of the IDHM considers life expectancy at birth, that is, the average number of years that people living in a certain place would live from birth, keeping the same mortality patterns observed in each period. Life expectancy at birth summarizes the social, health and salubrity conditions of a population when considering the mortality rates in its different age groups. All causes of death are considered to arrive at the indicator,	2010	0,334599248	gain	Dimensionless index

			both diseases and external causes, such as violence and accidents.				
Per capita health spending	Health	1.a	Expenses arising from actions aimed at ensuring public health per capita	2013	0,330920651	gain	$ per capita
Per capita electricy consumption	Service	7.1	Total electricity consumption in MWH divided by the total population.	2010	0,207856978	cost	MWH per capita
Persons per internet subscriber	Service	17.8	Scores that were calculated from: Fixed-line network and internet - Percentage of households that have access to the fixed-line network and internet.	2012	0,207823214	gain	Dimensionless index
Working in manufacturing industry	Service	9.2	Percentage of jobs in the Transformation Industry activity	2010	0,206930705	gain	% of jobs in the Transformation Industry activity
Water consumption	Service	6.1	Average consumption per capita of water L/HAB/DAY	2018	0,208746774	cost	Liter/population/day
Artificial Surface Area	Service	11.3	Represents the urbanized area of a region in relation to the total land area	2010	0,168642329	cost	% the total land area
Per capita net income of farmers	Well-being	2.3	Farmers' net income per capita	2017	0,169658469	gain	$ per capita
Water density (water area/total)	Well-being	6.3	Area occupied by water divided by the total area of the county	2010	0,201650005	gain	% of total area of the county
Crime rate	Well-being	16.3	The Security dimension of the Municipalities Performance Index (IDM-Security) was calculated through the simple arithmetic mean of the standardized scores from 0 to 10 of the variables related to the number of occurrences of the following types of crimes: Crimes against sexual dignity - occurrences to every 100 thousand inhab.; Crimes against the person - occurrences per 100,000 inhab.; Crimes against property - occurrences per 100,000 inhab.; Criminal misdemeanors (illegal possession of weapons, disarmament statute	2012	0,216674173	gain	Dimensionless index

			and possession of drugs for personal use) - occurrences per 100,000 inhab. and Drug trafficking - occurrences per 100,000 inhab.				
Household Disposable Income	Well-being	10.1	Average value of total monthly household income per nominal capita	2010	0,21635221	gain	$ per house
Green space index	Well-being	15.1	Percentage green space (vegetation area/total urban area)	2010	0,195665143	gain	% of total urban area

6 FINAL CONSIDERATIONS

Based on scientific evidence that GIS has emerged as a trend in research involving the theme of sustainability, whether promoting or evaluating the state of sustainable development, we decided to carry out a sequence of studies to contribute to this debate, answering a central question of this research, that is: How can a Geographic Information System act in the Sustainability Assessment processes? To adequately answer this question, we understand that it is necessary to identify the theoretical bases and methodological guidelines for an SA supported by GIS, as well as to point out the recurring challenges of its application.

To achieve this objective, a series of four studies was developed. Table 6.1 includes a matrix with the main conclusions, contributions to knowledge advancement, and limitations of each work. However, we describe the conclusions below in detail, which make some inferences and interconnect the research.

In the first study, we achieved the objective of identifying sustainability approaches that are historically applied in GIS-supported SA work. Therefore, we identified that there is a predominance of perceiving sustainability from an ecological/environmental perspective in studies on this topic. This inference is strengthened because we find that GIS tools are usually combined with products derived from remote sensing, especially to determine changes in land use and occupation. For work in which the number of variables is intensified and their spatial characteristics are indispensable, these tools are integrated with multicriteria analysis techniques, which supports spatial decision making.

The second study is presented as a complement to the previous one, as it aims to understand more broadly the thematic fields in which geospatial tools act in SA, based on a bibliometric analysis. The results strengthened what we had already concluded in the previous stage, that is, sustainability had a unidimensional character, focusing mainly on themes that focused on environmental mapping (i.e., land use, characterization of urban expansion, risk and vulnerability assessments environmental). However, when we consider the publications from a temporal fraction, we identify that there is a trend of evaluations that extrapolate the environmental aspects and start to perceive sustainability from a multidimensional vision, that is, they integrate other dimensions, such as social and economic. Furthermore, this bibliometric study also allowed us to identify that these multidimensional assessments would be strongly guided by the global targets and goals of sustainable development defined by the 2030 Agenda.

Among the results obtained in the previous stages, we highlight the fact that the SA supported by the GIS is concentrated mainly on regional/local scales and that they tend to have a sustainability approach based on a multidimensional concept. In view of this, we carried out the third study in which we developed a bibliographical review with the objective of discussing different operational particularities of regional sustainability assessments, contextualizing the spatial issue. This work pointed to methodological ways to overcome challenges that we consider essential in the operationalization of the evaluation and that aim to fill some gaps identified in this field of research. Thus, we highlight the great importance of obtaining an evaluation process in which the indicators allow for an interregional and intraregional analysis, that is, the set of variables must contain common and specific characteristics of the evaluated region, but at the same time have variables that are also common to other regions, in order to allow comparative analyses. These statements must be perceived from two equally important observations: (1) To meet these requirements, the set of indicators applied in the regional assessment should not be fixed, considering that regional particularities must be met; (2) the use of geospatial data, geoprocessing techniques and tools, and remote sensing products can be fundamental to represent these particularities, mainly in the environmental dimension.

After the stages in which conceptual bases were discussed and a series of methodological guidelines were unveiled, we decided to develop the fourth and last study, in which we aimed to broaden the discussion on the approach to SA on regional scales, proposing and applying a geospatialized performance evaluation structure for sustainability, which we tried to guide by the main guidelines obtained in previous studies. Thus, the results showed an inclusive framework in human-nature relations, since it has the characteristic of integrating different dimensions. In addition, the use of indicators that were constructed from remote sensing techniques gives the framework the condition to assess sustainability (or performance for sustainability) based on specific environmental information from the locations that make up the region, and with temporal flexibility of the data. Finally, the polyvalence provided by the multicriteria spatial decision support model SSAM (Spatial Sustainability Assessment Model), which, with full integration with GIS, provides an SA that adapts to different scales, through a transparent process, where the user is fully aware of the calculations performed and promotes a spatialized analysis of the results.

In this way, and after completing all the steps, we can infer that the use of GIS has the potential to fill important gaps such as flexibility in geographic scalability; flexibility in temporal scalability; and simplification of the presentation of results in the form of maps, which, in addition to supporting decision makers and policy makers, promotes the participation of stakeholders in the evaluation process, making it easier for society as a whole to understand the region's performance toward sustainability.

Furthermore, it is necessary to recognize the versatility of geospatial tools, which in the last 30 years have been supporting works aimed at evaluating the effects of anthropic activity in nature. Although there is a less comprehensive view of sustainability, the importance of these studies in the discussion of the preservation of important resources for humanity, such as water resources, soil, and forests, should be considered. On the other hand, different studies aim to calculate different indices, which, although not one-dimensional, are in charge of assessing socioeconomic performance in isolation, but are equally important. However, GIS, and its related areas, such as remote sensing, emerge as instruments that potentially integrate these different dimensions, transforming segmented measurements into globalizing assessments.

Table 6.1 Matrix of individualized conclusions.

Title of the study	**PARTICULARIZED CONCLUSION**		
	Main conclusion	***Contribution to the advancement of knowledge***	***Limitations***
Trends in sustainability assessment supported by geographic information systems: a bibliometric approach	GIS-supported research in SA addresses sustainability primarily from an ecological perspective, and the use of GIS tools and remote sensing products predominates, mostly at a regional or local scale. When integrated with MCDA techniques, they focus on solving decision problems in which the spatial variable is indispensable.	The main contribution is the expansion of knowledge about SA supported by GIS, which is a field of analysis on the rise.	Limitation due to the use of only the Scopus database, which may have ignored studies that would contribute to the discussion.
Geographic information system applied to sustainability assessments: conceptual structure and research trends	There is a trend towards multidimensional approaches where SD Goals and Targets have become guides for GIS supported SA.	It provided important information about the sources that stand out to be consulted, and points out directions for future work.	Limitation due to the use of only the Scopus database, which may have ignored studies that would contribute to the discussion.
Operationalizing the regional sustainability assessment by indicators	Multilevel interaction is addressed through regional indicators applied to all regions, allowing comparability. Participatory stakeholder approach, aligning with the most important regional issues. The use of geospatial data, geoprocessing techniques and tools, and remote sensing products can be fundamental.	Important challenges inherent to regional SA were discussed, as well as gaps that still need to be considered in future work.	There is the limitation that the text reflects the point of view of the authors when pointing out the methodological approaches that they consider essential for the discussion of the theme.
Performance towards sustainability: a regional assessment supported by the GIS	The application of the proposed framework demonstrated that its theoretical and methodological design is comprehensive in human-nature relations, flexible in criteria and their temporalities, transparent in the methods and mathematical models used and democratic in terms of communicating results.	The presented proposal indicates a path to be considered in future research on regional sustainability, with opportunities in the use of GIS in different stages of the evaluation process.	The non-participation of stakeholders in the process of selection and weighing of indicators may not translate the interpretation of sustainability supported by the population that lives there.