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Fuzzy-based Support System for Urban Green Infrastructure Management

Sistema Fuzzy de Apoio à Gestão da Infraestrutura Verde Urbana

Adriano Bressane[*], Leonardo Massato Nicácio Nomura[**], Felipe Hashimoto Fengler[***], Líliam César de Castro Medeiros[****], Rogério Galante Negri[*****]

[*]Department of Environmental Engineering, São Paulo State University, adriano.bressane@unesp.br
[**]Department of Environmental Engineering, São Paulo State University, leonardo.nomura@unesp.br
[***]Department of Civil Engineering, Sorocaba Engineering School, felipe.fengler@facens.br
[****]Department of Environmental Engineering, São Paulo State University, liliam.medeiros@unesp.br
[*****]Department of Environmental Engineering, São Paulo State University, rogerio.negri@unesp.br

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Abstract

Dealing with the challenges of rapid urban growth while preserving ecological ecosystems and human quality of life is a hard task and a cornerstone of sustainable urban development. This study proposes a Decision Support System (DSS) for the management of Urban Green Infrastructure (UGI). The DSS was developed using fuzzy artificial intelligence to address uncertainties inherent in the integration of geospatial data within the computational environment of a Geographic Information System. The selection of variables and configuration parameters was based on a literature review and expert consultation through the Delphi method. To verify the potential of the DSS, a case study was developed in the Biological Reserve of Serra do Japi. The results indicate that the DSS serves as a promising tool for planners, policymakers, and researchers, capable of supporting data-driven recommendations through case-by-case analyses. Future research could explore the integration of additional indicators, enhance the inference mechanism, and extend the application of the DSS across diverse urban contexts to optimize its versatility and effectiveness in UGI management.

Keywords:
Green Infrastructure, Sustainable Cities, Fuzzy Logic, Artificial Intelligence.

Resumo

Enfrentar desafios do rápido crescimento das cidades, enquanto se preserva os ecossistemas e a qualidade de vida humana, é um desafio complexo para o desenvolvimento urbano sustentável. Este estudo propõe um Sistema de Suporte à Decisão (SSD) para a gestão da Infraestrutura Verde Urbana (IVU). O SSD, desenvolvido com base em inteligência artificial fuzzy, foi projetado para lidar com incertezas inerentes à integração de dados geoespaciais no ambiente de um Sistema de Informação Geográfica. A seleção das variáveis e parâmetros foi realizada por meio de revisão da literatura e

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consulta a especialistas utilizando o método Delphi. Para verificar o potencial SSD, foi realizado um estudo de caso sobre uma bacia hidrográfica localizada na Reserva Biológica da Serra do Japi. Os resultados indicam que o SSD constitui uma ferramenta promissora para planejadores, formuladores de políticas e pesquisadores, a qual oferece suporte a recomendações orientadas a dados e derivadas de análises de casos. Pesquisas futuras devem explorar a integração de indicadores adicionais, aprimorar o mecanismo de inferência fuzzy e estender a aplicação do SSD em diversos contextos urbanos.
Palavras-chave:
Infraestrutura Verde, Cidades Sustentáveis, Lógica Fuzzy, Inteligência Artificial.

I. INTRODUCTION

In the contemporary context of rapid and unplanned urban expansion, cities are increasingly confronted with critical challenges, notably the fragmentation of natural ecosystems. Such fragmentation detrimentally affects environmental quality and exacerbates living conditions within urban environments (LIMA et al., 2022; ASSEDE et al., 2023; ZHENG et al., 2023). The ensuing complexity from the nexus between natural resource conservation and land use and cover (LULC) management intensifies crises impacting food security and human well-being (NÄSCHEN et al., 2019; KARIUKI et al., 2021; CUI et al., 2022).

In response to the challenges of urban growth, the concept of greener cities has emerged, aiming to harmonize urban expansion with ecological preservation (BLASI et al., 2022; DEMIREL, 2023). As part of this transformation, Urban Green Infrastructure (UGI) has developed as a strategic approach. This involves a network of natural and semi-natural spaces, including forest fragments, urban parks, gardens, and green corridors, all strategically planned and managed to provide essential ecosystem services. UGI is intended to foster resilient and livable environments, contributing to climate change mitigation, improved air and water quality, and enhanced urban biodiversity (ZHANG et al., 2022; BLASI et al., 2022; DEMIREL, 2023).

Recent studies have focused on the challenges and strategies for managing UGI, aiming to support water resource preservation, heat island mitigation, climate risk reduction, food security, and energy efficiency (FLORES et al., 2021; OU et al., 2022; OLIVEIRA et al., 2022; LIN et al., 2023). Efforts have been dedicated to the development of Decision Support Systems (DSS) for various applications, such as urban tree management and participatory green space management (BRESSANE et al., 2018; LANGEMEYER et al., 2020; ZAREI; NIK-BAKHT, 2021; MASSARO et al., 2021; CARVALHO MARIA et al., 2023).

This study developed a DSS tailored to the sustainable management of UGI, based on integrated analysis of geospatial data within a Geographic Information Systems (GIS) computing environment. A DSS is a tool that aids in complex decision-making by integrating data, analytical models, and logical rules. These systems are

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crucial for the efficient management of UGI, enabling analyses and simulations based on multiple environmental and urban variables. Various types of DSS exist, including those based on artificial intelligence (AI), statistical models, and fuzzy logic, each suited to different data complexity and uncertainty scenarios.

To address the inherent uncertainties in the indirect acquisition of spatial data, particularly when sourced from multiple origins (LIU et al., 2018), subject to variations in scale, reference systems, and equipment precision (NIKIFOROVA et al., 2019), which can be analog or digital with different forms of representation (ZHOU et al., 2018), the proposed DSS in this study employs fuzzy logic. This choice is due to fuzzy logic's ability to handle uncertainties and provide a more intuitive and adaptive modeling of human reasoning, facilitating the integration of complex data and the formulation of precise recommendations for managing UGI.

Specifically, due to its recognized ability to handle uncertainties, fuzzy logic has been widely used in the construction of environmental management systems to support complex decision-making, such as evaluating environmental impacts, participatory diagnostics, land-use planning, resource allocation and optimization, and environmental risk management (BRESSANE et al., 2016; BRESSANE et al., 2017; MOTA et al., 2019; SILVA et al., 2020; EWBANK et al., 2020; BRESSANE et al., 2022; BRESSANE et al., 2022; BRESSANE et al., 2023a; BRESSANE et al., 2023b).

Therefore, the aim of this study was to propose and evaluate the capability of the DSS to support decision-making related to the sustainable management of urban green spaces, considering environmental, urbanistic, and social variables to promote urban resilience, improve the quality of life of populations, and mitigate the effects of climate change in cities.

II. Materials and Methods

The development of the proposed DSS is grounded in the integration of three Fuzzy Inference Systems (FIS) within a GIS environment, specifically utilizing QGIS software. The selection of variables for the DSS was based on a thorough literature review using databases such as Web of Science, Science Direct, and Scopus. Search terms used included: title-abs-key (("green infrastructure" OR "green space" OR "green building") AND ("smart city" OR "sustainable city" OR "healthy city") AND ("artificial intelligence" OR "fuzzy logic" OR "machine learning")) AND (limit-to (pubstage, "final")) AND (limit-to (doctype, "ar")) AND (limit-to (subjarea, "eng." OR "env.")) AND (limit-to (pubyear, "2015 to 2024")). This search yielded 172 articles, from which 12 pertinent studies were selected after screening for relevance. These studies not only define the theoretical framework for the proposed system but also highlight advancements made by previous research and set a foundation for the

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innovative contributions of this study.

During the fuzzification stage, system variables were categorized using linguistic values. Unlike DSS based on classical logic, the developed FIS provides a mechanism to mathematically handle uncertainties through gradual transitions between values using triangular membership functions, which are widely used in similar studies (JAIN; SHARMA, 2020). The second stage involved constructing the rule base using Type-1 FIS, known for its expressive power and enhanced capability to handle uncertainties. Type-1 FIS is commonly utilized across various applications due to its flexibility and lower computational cost (SILVA et al., 2020). This setup allows the DSS to emulate human reasoning processes by capturing the essence of how experts make decisions (BRESSANE et al., 2017).

The parameters and rules for the DSS variables, as well as the rules applied in the FIS, were established through an expert committee using the Delphi technique. In this method, each expert independently submits proposals which are then synthesized by a facilitator (HSU; SANFORD, 2019). Subsequently, the committee members discuss and analyze a synthesis report, refining their proposals in subsequent rounds until consensus is reached. This process was conducted anonymously, enabling experts to express their views and engage in high-level, unbiased discussions.

III. RESULTS AND DISCUSSION

Literature review

A synthesis of the studies reviewed is provided in Table 1. For each reference, the developed approach and the contributions of the study to the field of UGI management are summarized. This synthesis establishes a foundation to demonstrate the originality and advancements intended with the proposed DSS in the current study.

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Table 1 - Literature Review Synthesis.

	Developed Approach	Contribution to the Field
Oliveira et al. (2022)	Exploration of the potential of Urban Green and Blue Infrastructure, emphasizing its role in ecosystem services and resilience.	Supports sustainability, water and food security, reduces energy consumption, and contributes to the circular economy.
Bibri (2021)	Integration of urban processes in smart cities focused on data-driven technologies and data analysis.	Comprehensive exploration of urban paradigms and the transformative impact of data science on land use planning and management.
Flores et al. (2021)	Investigation of the role of regional governments in water-sensitive practices in UGI.	Addresses specific challenges in UGI implementation with a focus on regional governance.
Bressane et al. (2018)	Optimization of urban tree management using AI tools for risk assessment and effective tree management.	Focuses on efficient urban arboriculture management, using artificial intelligence to improve management practices.
Lin et al. (2023)	Machine learning to examine the relationship between the spatial pattern of UGI and heat island intensity.	Insights for Land Use and Cover planning considering the relationship between UGI and heat islands.
Ou et al. (2022)	Proposal of a method for spatial prioritization of UGI, addressing risks from ecosystem degradation and climate change.	Incorporates states of vulnerability and risk to prioritize UGI management zones based on biodiversity and ecosystem services.
Massaro et al. (2021)	DSS to optimize UGI planning considering climatic conditions and occupancy patterns.	Focuses on optimizing the design of UGI, integrating climate and occupancy data to support planning decisions.
Langemeyer et al. (2020)	Bayesian networks to assess the demand for ecosystem services of green roofs.	Provides a spatial model to guide effective municipal policies for UGI.
Zhu et al. (2022)	Concept of a Happiness-Oriented Smart City, with an emphasis on efficient and public UGI.	Highlights human-centered development, including UGI as an essential component to promote happiness.
Barbosa et al. (2019)	Effective restoration in UGI designs based on biodiversity and ecosystem services.	Ecological restoration in UGI, integrating biodiversity and ecosystem services into an optimized design.
Bressane et al. (2017)	Fuzzy logic-based DSS for participatory diagnostics in UGI.	Community participation, integrating technical knowledge and local understanding through a fuzzy DSS.
Zarei and Nik-Bakht (2021)	Conceptual framework and a DSS for citizen engagement in urban projects, using fuzzy sets and a fuzzy inference mechanism.	Promotes citizen involvement in urban management, using fuzzy logic to address uncertainties.

(Source: author 1)

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The review of prior studies has underscored significant advancements in the management of UGI. These studies have ranged from enhancing urban resilience to optimizing UGI design, occasionally integrating AI and machine learning technologies. However, a critical gap has been identified: the absence of a DSS for sustainable UGI management that is informed by geospatial data on resilience, vulnerability, and disturbance levels of the targeted areas, as proposed in this study.

UGI Management Support System

The first system (FIS1) was developed for the integrated analysis of the variables "Size" and "Edge Effect," resulting in the "Fragility Index" of the UGI (Figure 1, Table 2). The selection of these variables and the formulation of rules that delineate their interrelationships were based on the understanding that larger UGI fragments with a more circular shape tend to offer better resistance to stressors, enhanced habitat diversity, increased biodiversity, and ecosystem stability (GUARIS et al., 2020).

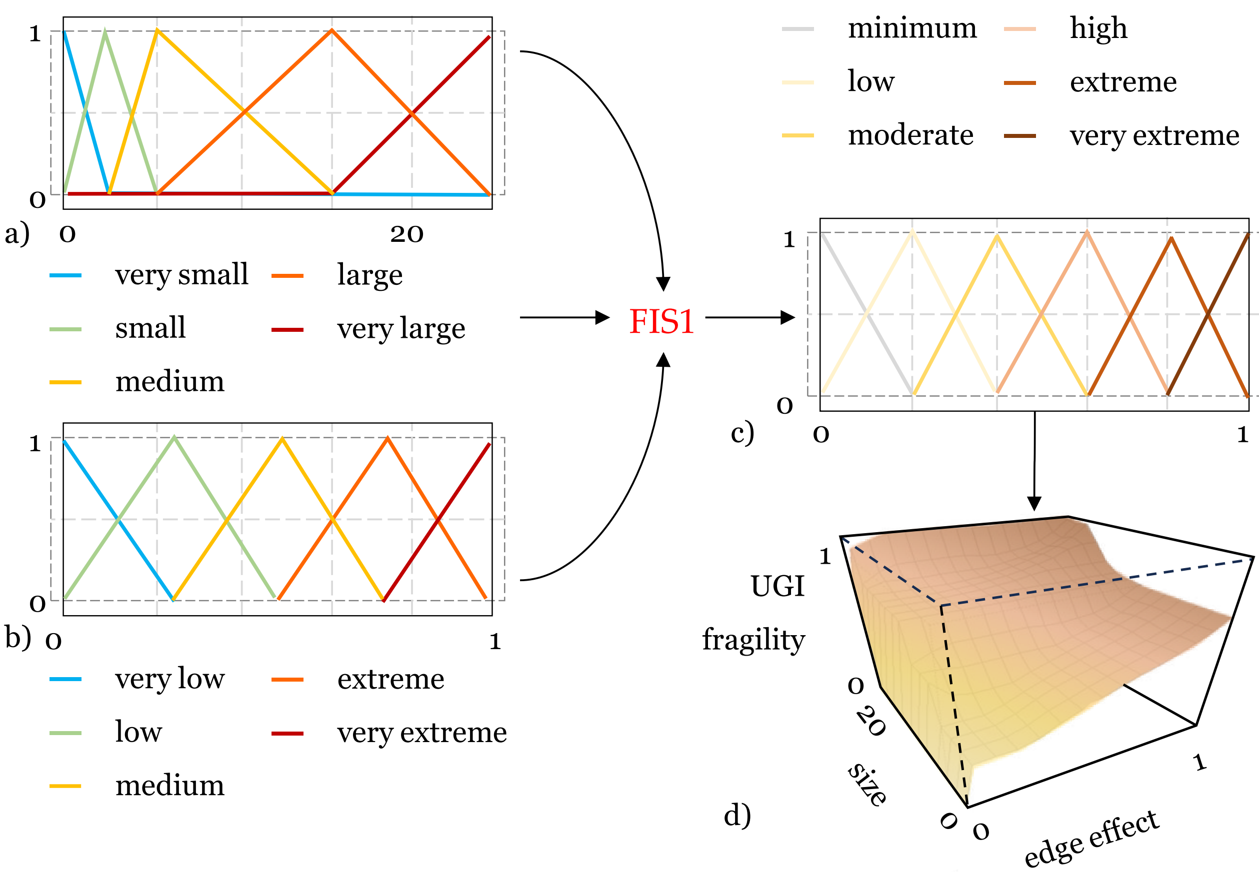

Figure 1 - FIS1: a) Size of UGI; b) Edge Effect of UGI; c) UGI Fragility Index; d) decision surface (Source: author 1).

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Table 2. UGI Fragility based on rule basis of FIS1.

		Edge Effect				
		Very Low	Low	Medium	High	Very High
Size	Very Small	Moderate	High	Extreme	Very Extreme	Very Extreme
	Small	Low	Moderate	High	Extreme	Very Extreme
	Medium	Low	Low	Moderate	High	Extreme
	Large	Minimal	Low	Low	Moderate	High
	Very Large	Minimal	Low	Low	Low	Moderate

(Source: author 1).

The second system (FIS2) utilizes the variables "Connectivity" and "Support Capacity" to compute the "UGI Resilience Index" (Figure 2, Table 3). The logical framework applied in FIS2 posits that strong connectivity and high support capacity are crucial for sustaining genetic flow, effective species movement, nutrient exchange, and the propagation of ecological functions (ABREU et al., 2014; SILVA et al., 2019).

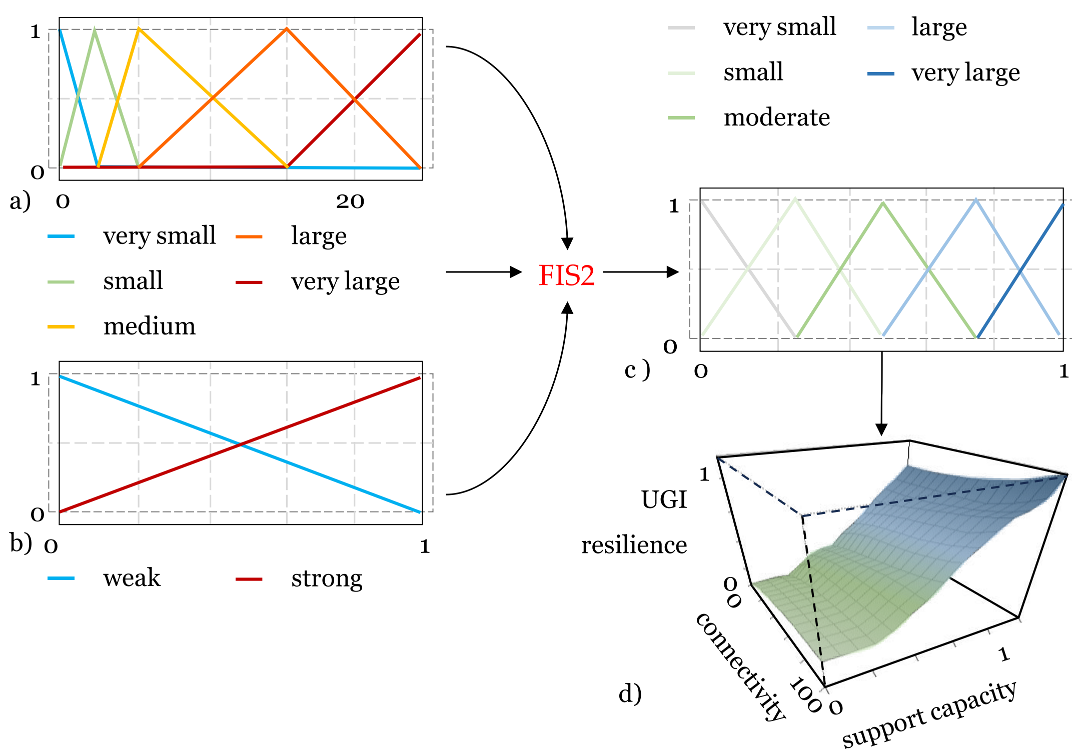

Figure 2 - FIS2: a) Connectivity; b) Support Capacity; c) UGI Resilience; d) decision surface (Source: author 1).

Table 3 - UGI resilience based on Rule basis of FIS2.

Connectivity	Support Capacity	Resilience Index

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Very Small	Strong	Small
Very Small	Weak	Very Small
Small	Strong	Small
Small	Weak	Very Small
Medium	Strong	Moderate
Medium	Weak	Small
Large	Strong	Large
Large	Weak	Moderate
Very Large	Strong	Very Large
Very Large	Weak	Moderate

(Source: author 1).

The FIS3 combines the outputs from FIS1 and FIS2 to derive the "UGI Sustainability Index," which assesses the capacity of the UGI to sustain itself over varying time frames (Figure 3, Table 4). This index provides a view of UGI's longevity and resilience in maintaining ecological functionality under varying urban conditions. FIS3 overlays the sustainability condition with existing disturbance factors, such as LULC. It employs fuzzy "OR" and "GAMMA" (γ = 0.5) operations within the GIS. This integration allows the DSS to generate sustainable management recommendations for UGI (Figure 4, Table 5).

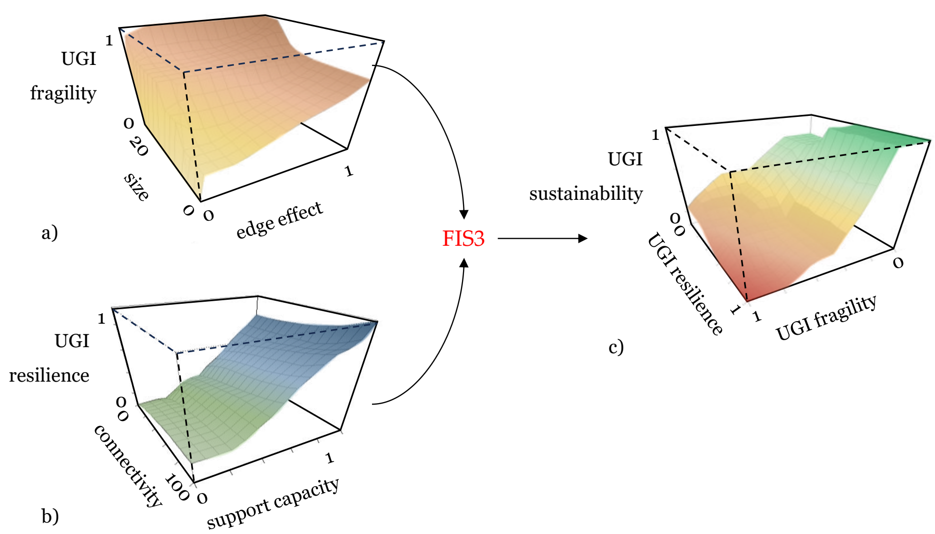

Figure 3 - FIS3: a) UGI Fragility Index; b) UGI Resilience Index; c) UGI Sustainability Index (Source: author 1)

Table 4 – UGI sustainability based on rule basis of FIS3.

	Resilience				
	Very Small	Small	Moderate	High	Very High

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Fragility	Minimal	Medium Term	Medium Term	Medium Term	Long Term	Very Long Term
	Low	Medium Term	Medium Term	Medium Term	Long Term	Very Long Term
	Moderate	Short Term	Short Term	Medium Term	Long Term	Long Term
	High	Very Short Term	Short Term	Short Term	Medium Term	Long Term
	Extreme	Very Short Term	Very Short Term	Short Term	Medium Term	Medium Term
	Very Extreme	Very Short Term	Very Short Term	Very Short Term	Short Term	Medium Term

(Source: author 1).

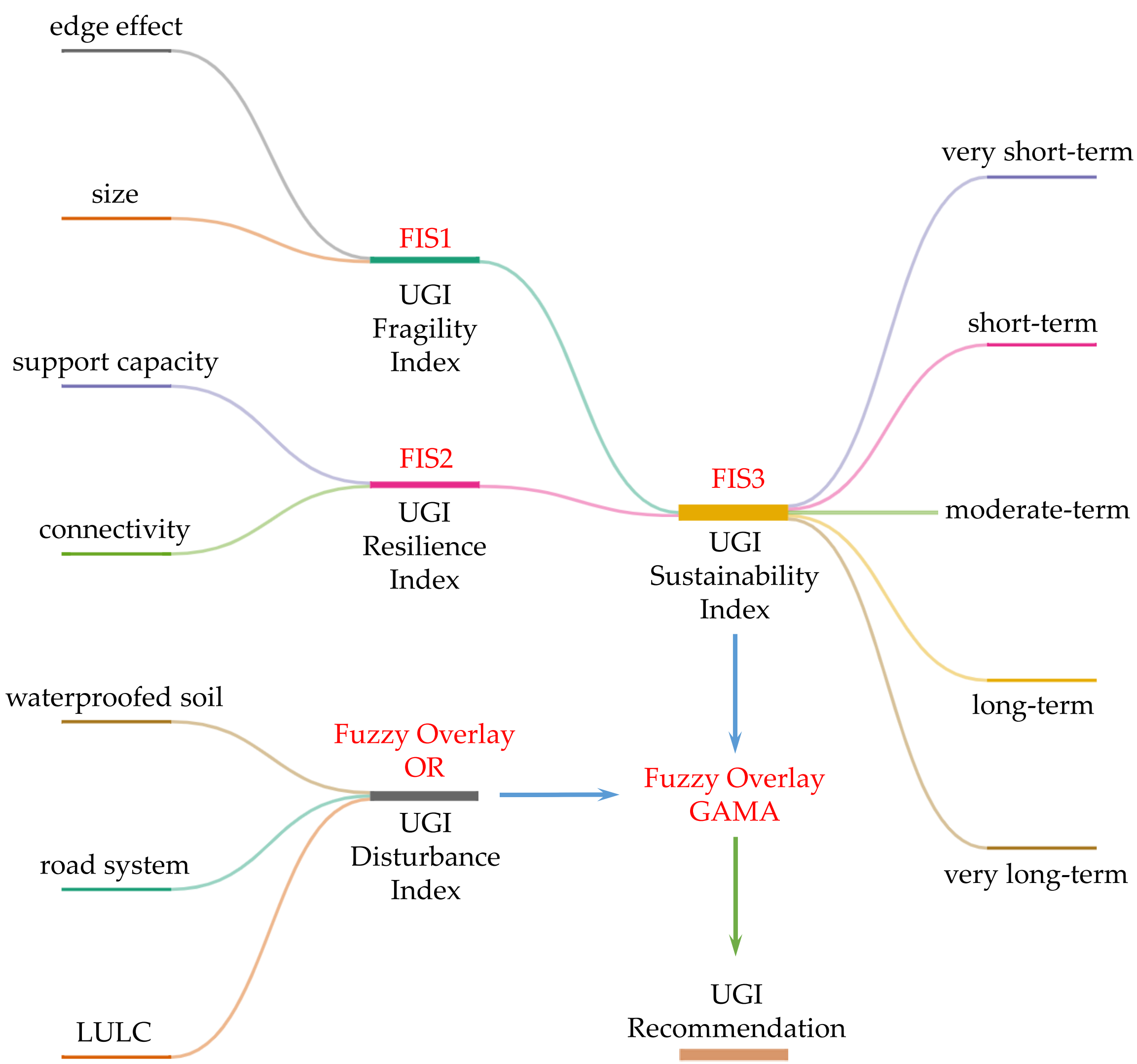

Figure 4 – Fuzzy AI-based decision support system framework (Source: author 1).

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Table 5 – Recommendations to UGI management.

FIS3 Output	Assessment	Recommendation
[0.8, 1.0]	UGI with very long-term sustainability; conditions resembling a natural state.	(i) Create buffer zones around UGI to mitigate potential external disturbances and safeguard its integrity against urban expansion; (ii) Implement regular biodiversity monitoring to assess the health and diversity of flora and fauna, identifying any changes that may require intervention; (iii) Engage local communities through educational programs to increase awareness of the ecological importance of UGI, fostering a sense of responsibility; (iv) Prioritize natural regeneration techniques, reducing human intervention and allowing the ecosystem to restore over time.
[0.6, 0.8[	UGI with long-term sustainability; minor effects from disturbances, conservation elements prevailing.	(i) Establish ecological corridors connecting altered areas of UGI to promote genetic exchange and facilitate the movement of flora and fauna within the urban landscape; (ii) Implement targeted restoration efforts to enhance biodiversity and ecological functions, including reforestation, invasive species management, and habitat enhancement; (iii) Zoning regulations that prioritize UGI preservation, ensuring that nearby developments do not invade or further degrade its integrity; (iv) Integrate UGI into urban planning, creating multifunctional spaces that balance human needs with ecological preservation.
[0.4, 0.6[	UGI with medium-term sustainability; impacted state from disturbances, limited conservation.	(i) Restore degraded areas by prioritizing replanting with native plant species, aiming to reestablish ecosystem functionality and promote biodiversity; (ii) Execute invasive species control plans to mitigate the spread of non-native species that could further degrade the ecological integrity of moderately altered UGI; (iii) Establish green corridors and links connecting UGI areas, fostering genetic flow and improving movement opportunities for fauna in urban areas; (iv) Integrate UGI into urban planning frameworks, ensuring that surrounding development considers its ecological value; (v) Engage local communities through participatory programs, educating residents on the importance of UGI and involving them in conservation efforts.
[0.2, 0.4[	UGI with short-term sustainability; exhibits strong effects from sources of disturbance.	(i) Rehabilitate these highly altered UGI areas by reintroducing native species and restoring natural ecosystem functions; (ii) Implement UGI design techniques leveraging technological solutions to enhance ecosystem services, such as stormwater management, air purification, and noise reduction; (iii) Strategically execute urban reforestation initiatives targeting the establishment of native vegetation within altered UGI areas to enhance biodiversity and ecosystem resilience; (iv) Construct habitat improvements, like nesting sites for birds and habitats for insects, to promote the return of biodiversity and support the reestablishment of ecosystem processes; (v) Perform a comprehensive assessment of the ecosystem services provided by these altered UGI areas, quantifying their benefits to the urban environment and advocating for their preservation.
[0.0, 0.2[	UGI with very short-term sustainability; under extreme effect from sources of disturbance.	(i) Develop comprehensive ecosystem restoration plans that emphasize the use of native plant species and focus on restoring ecological processes that support the reestablishment of essential ecosystem functions; (ii) Implement advanced ecological infrastructure solutions, such as biofiltration systems and artificial wetlands, to mitigate the impacts of altered vegetation, improving water quality and urban climate regulation; (iii) Design and implement habitat creation initiatives catering to specific wild species adapted to urban conditions, aiming to support local biodiversity and promote habitat connectivity; (iv) Transform highly altered UGI areas into regeneration projects of degraded areas, utilizing innovative techniques to revitalize these spaces while integrating sustainable land uses; (v) Launch comprehensive public engagement campaigns to raise awareness of the critical need to preserve and rehabilitate these altered UGI areas, involving communities in active restoration efforts.

(Source: author 1).

Case study

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To demonstrate and discuss its potential, the proposed system was applied to the analysis of UGI in the Jundiaí-Mirim river basin, which is considered an integral part of the UGI network. This basin includes a network of natural and semi-natural spaces capable of providing ecosystem services such as climate regulation, water and air purification, and spaces for recreation and biodiversity conservation. The Jundiaí-Mirim river basin is located in the Biological Reserve of Serra do Japi, in the city of Jundiaí, São Paulo (SP), Brazil, an area of significant environmental and urban interest (Figure 5).

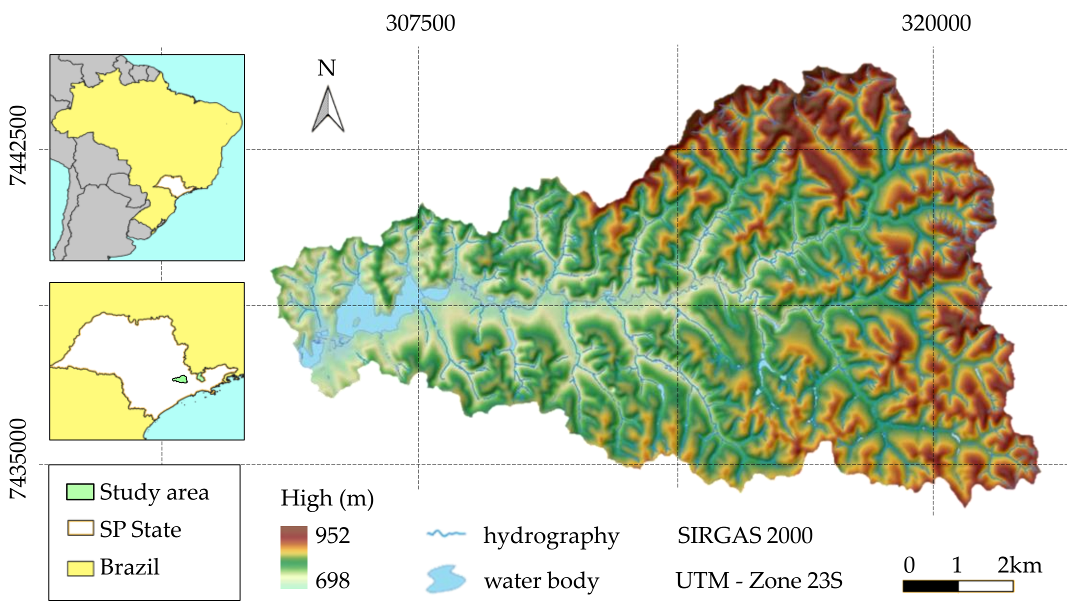

Figure 5 – The study area - Jundiaí-Mirim river basin (Source: author 1).

Despite being located in the buffer zone of the Serra do Japi Biological Reserve—an area granted special protection—the region has experienced significant environmental pressures due to the increasing encroachment and suppression of its forest remnants over recent decades. This presents a critical scenario that necessitates focused attention on sustainable land use management (LIMA et al., 2023). For this case study, a comprehensive database was utilized, including aerial and orbital imagery along with geospatial data on land use and cover. This data was organized in vector format (i.e., shapefile), ensuring interoperability across various GIS platforms. Subsequently, synthetic maps consisting of landscape metrics such as edge effect and area size for analyzing UGI fragility, support capacity and connectivity for resilience analysis, and the mapping of disturbance sources (impervious surfaces, roadway systems, land use, and cover) in the area were generated through geoprocessing (Table 6).

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Table 6 – Weighting of disturbance sources associated with LULC.

LULC	Weight*	LULC	Peso*
Agroindustry	0.1	High-density Housing	0.1
Agricultural Crops	0.5	Low-density Housing	0.1
Woodland	0.8	Pasture	0.5
Lawn	0.3	Pasture with Exposed Soil	0.3
Industrial	0.1	Overgrown Pasture	0.6
Industrial Subdivision	0.1	Fish Farming	1.0
Residential Subdivision	0.1	Reforestation	1.0
Thicket	0.9	Dam	1.0
Forest	1.0	Silvopasture	0.7
Mining	0.1	Exposed Soil	0.1
Mining Recovery	0.2	Floodplain	1.0

*This range from 0.1 to 1.0, where values closer to 1.0 signify a lower potential for disturbance (Source: author 1).

The landscape metrics used in this analysis included calculating distances between forest fragments and sources of disturbance, which were normalized on a scale from 0 (fragments directly adjacent to disturbance sources) to 1 (fragments located 200 meters or more away). The support capacity was classified considering the potentials and constraints related to land use. A radius of 100 meters around all UGI units was established to construct the connectivity indicator, linking distances to the nearest unit. Greater isolation corresponded to more adverse local resilience conditions. The size of each UGI unit was calculated, and the Euclidean distance within a 30-meter buffer zone simulated the decay effect of disturbance as the distance from the source increases. The edge effect of the UGI was determined by calculating its circularity. The main results are presented in Figure 6.

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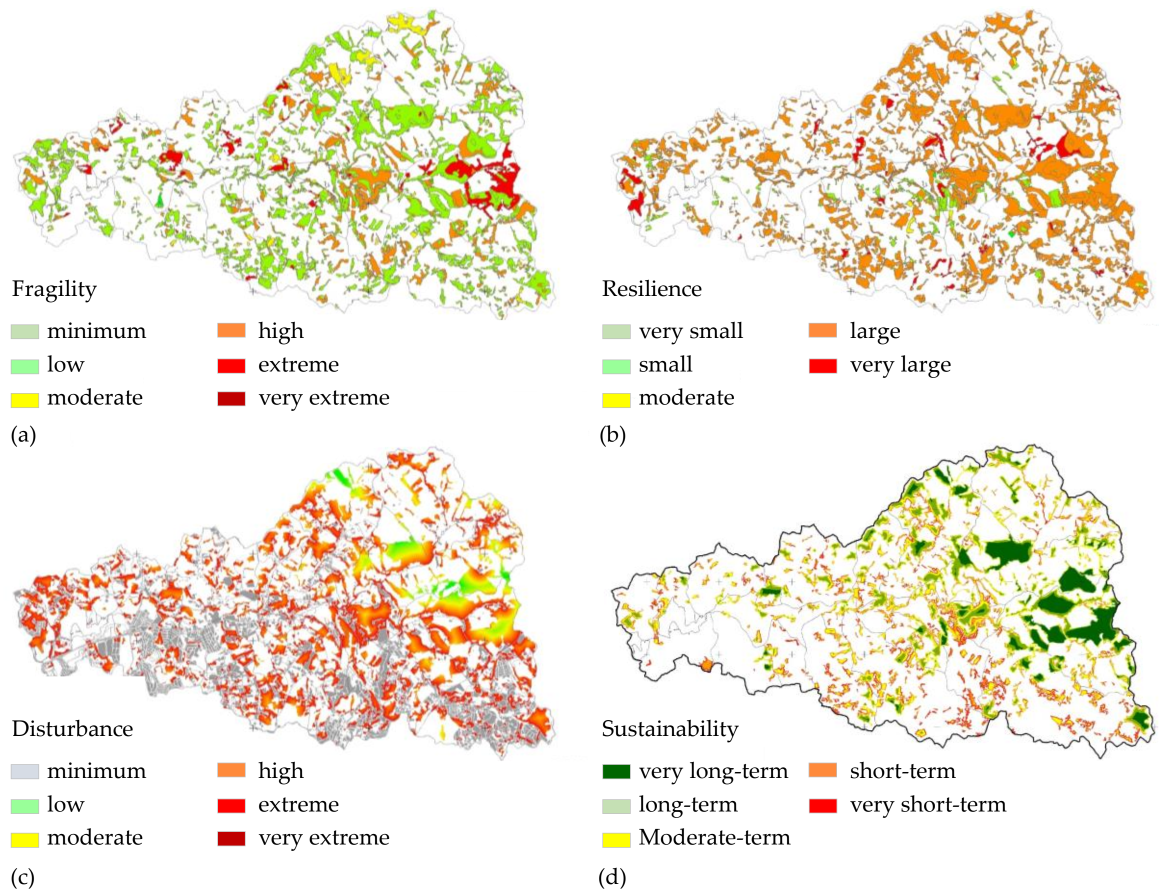

Figure 6 – Classification of UGI regarding the: (a) fragility from FIS1, (b) resilience from FIS2, (c) disturbance from fuzzy overlay - OR, and (d) sustainability from FIS3 (Source: author 1).

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Following the application of the proposed DSS to the case study, 18 experts were consulted to validate the system. These experts were selected based on their experience in the environmental field, including academics, professionals from the public and private sectors, and specialists in various roles. Validation was conducted through an electronic form that addressed the relevance and suggested modifications of the indicators, as well as the coherence and applicability of the model. The consultation indicated a consensus on the relevance of the indicators and the suitability of the model, noting that the results were generated coherently and effectively. Consequently, the outcomes provided by the proposed DSS were considered satisfactory, producing relevant classifications for homogeneous units and resulting in appropriate segmentation in cartographic synthesis procedures. As anticipated, it was observed that the results from FIS2 were influenced by the support capacity within each UGI unit, determined by the proximity of forest fragments within a specific reference perimeter. The vector-based analysis approach in the GIS environment also proved satisfactory during geoprocessing, adhering as expected to the pertinent restrictions on support capacity and the weighting of disturbance factors in the vicinity.

The fuzzy OR operator appropriately highlighted existing disturbances over the study area. This approach ensured that the resulting output not only incorporated the spatial particularities of the UGI but also robustly emphasized the conditions in its surroundings. As a result of integrating these intrinsic aspects of the UGI and its environment using the Fuzzy Overlay GAMMA operation, the proposed DSS yielded recommendations for the sustainable management of the UGI, which can be seen in the spatial representation of Figure 7.

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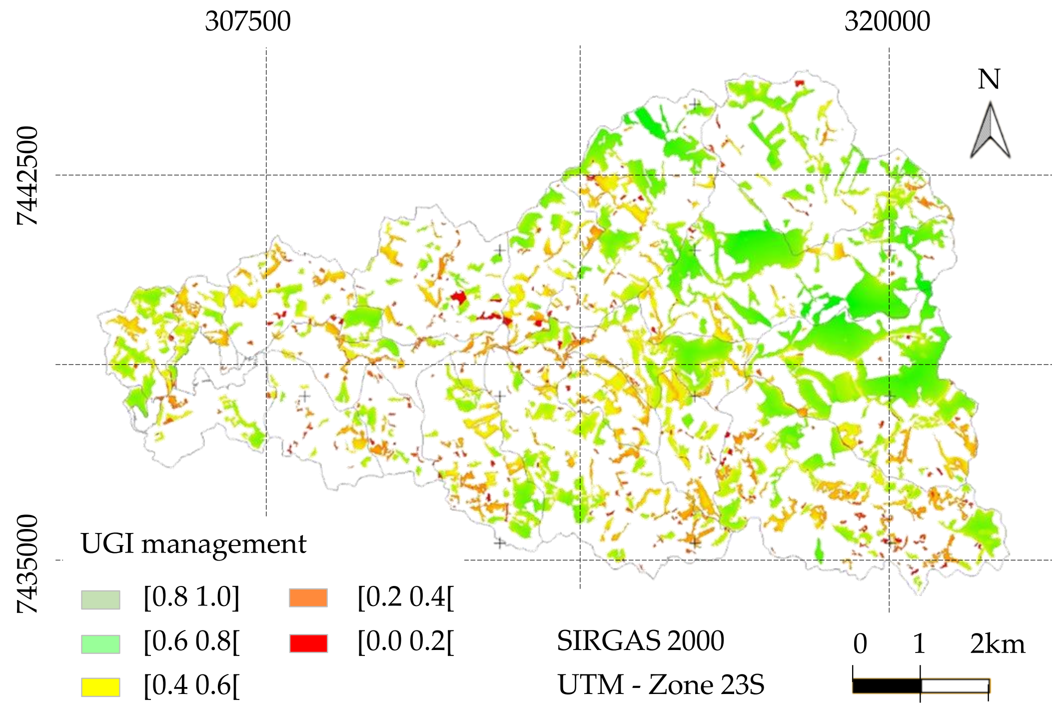

Figure 7 - Recommendations for sustainable management of UGI in the study area (Source: author 1).

The proposed DSS has demonstrated pertinent results, showcasing robustness and adherence to the principles of fuzzy logic within the realm of geospatial analyses. The system effectively integrates the influence of disturbance factors into the indicators of fragility and resilience, highlighting its potential as a viable tool for the sustainable management of UGI. However, while the case study has illustrated the capabilities of the proposed DSS, several limitations have been identified, which are discussed below.

As a current limitation, the DSS has been validated through expert consultation based on a single case study. This validation approach, while rigorous, limits the ability to generalize the DSS's performance across different urban settings. Future studies should aim to implement the DSS in a variety of urban scenarios. This broader application will help to verify its performance and robustness in diverse urban configurations, enhancing its adaptability and efficacy across different environmental and urban conditions.

Integrating data from multiple sources, a common necessity in urban environmental studies, involves challenges related to data precision, scale, and timeliness. These issues can significantly impact the accuracy and reliability of the analyses. It is crucial to address these challenges by comparing the DSS with other established models or methods. Such comparisons could provide further evidence of the reliability and practical

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applicability of the system. Continuously updating and verifying data sources will also be essential to maintain the accuracy and relevance of the DSS.

While the initial validations are promising, there is a need for ongoing testing and refinement to ensure that decisions based on the DSS are reliable and practically applicable in real-world settings. Implementing the DSS in real-life projects and continuously monitoring its outcomes will provide practical insights and help in fine-tuning the system. Collaborations with urban planners and environmental managers could facilitate these implementations, providing direct feedback from end-users and stakeholders.

IV. Conclusion

This study aimed to contribute to the complex challenge of sustainable UGI management. The AI-based fuzzy DSS has emerged as a promising tool, facilitating data-driven decision-making by providing strategic recommendations through case-by-case analysis. It is therefore reasonable to conclude that the proposed system holds potential to guide urban planners and public policy makers in fostering urban environments that maintain ecological balance while promoting social well-being and economic prosperity.

Future studies could enhance the DSS's scope by integrating new indicators and additional data sources. This expansion would allow for a more comprehensive analysis of UGI dynamics and provide a richer foundation for decision-making. Refining the existing fuzzy inference systems by considering more intricate relationships between variables could improve the accuracy and relevance of the recommendations. Delving deeper into the interactions between ecological, social, and economic factors can yield more nuanced insights. Extending the application of the DSS to different urban contexts would contribute to consolidating its validation, demonstrating its efficacy and versatility across various settings. This broader application would also test the DSS's adaptability and robustness, providing valuable feedback for further refinements. Effective implementation of the DSS's recommendations requires strong policy integration and active stakeholder engagement. Developing partnerships with local governments, community organizations, and environmental agencies will be crucial for translating DSS insights into actionable urban planning strategies. Establishing mechanisms for continuous monitoring and feedback can help in dynamically adjusting strategies based on real-time data and evolving urban conditions. This adaptive management approach will be essential for sustaining the relevance and effectiveness of the DSS in long-term urban and environmental planning.

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By addressing these future directions, the DSS can evolve into an even more robust tool, not only for assessing and managing the ecological aspects of UGI but also for integrating social and economic dimensions, thereby truly supporting sustainable urban development.

V. References

ABREU, K. M. P.; COUTINHO, L. M. Sensoriamento remoto aplicado ao estudo da vegetação com ênfase em índice de vegetação e métricas da paisagem. Revista Vértices, v. 16, n. 1, 2014, p. 177-202.

ASSEDE, E. S.; OROU, H.; BIAOU, S. S.; GELDENHUYS, C. J.; AHONONGA, F. C.; CHIRWA, P. W. Understanding drivers of land use and land cover change in Africa: a review. Current Landscape Ecology Reports, 2023, p. 1-11.

BARBOSA, A.; MARTÍN, B.; HERMOSO, V.; ARÉVALO-TORRES, J.; BARBIÈRE, J.; MARTÍNEZ-LÓPEZ, J.; IGLESIAS-CAMPOS, A. Cost-effective restoration and conservation planning in Green and Blue Infrastructure designs. A case study on the Intercontinental Biosphere Reserve of the Mediterranean: Andalusia (Spain)–Morocco. Science of the Total Environment, v. 652, 2019, p. 1463-1473.

BIBRI, S. E. Data-driven smart sustainable cities of the future: An evidence synthesis approach to a comprehensive state-of-the-art literature review. Sustainable Futures, v. 3, 2021, p. 100047.

BLASI, S.; GANZAROLI, A.; DE NONI, I. Smartening sustainable development in cities: Strengthening the theoretical linkage between smart cities and SDGs. Sustainable Cities and Society, v. 80, 2022, p. 103793.

BRESSANE, A.; GOMES, I. G.; DA ROSA, G. C. S.; BRANDELIK, C. C. M.; SILVA, M. B.; SIMINSKI, A.; NEGRI, R. G. Computer-aided classification of successional stage in subtropical Atlantic Forest: A proposal based on fuzzy artificial intelligence. Environmental Monitoring and Assessment, v. 195, n. 1, 2023a, p. 184.

BRESSANE, A.; GOULART, A. P. G.; MELO, C. P.; GOMES, I. G.; LOUREIRO, A. I. S.; NEGRI, R. G.; THOMÉ, R. F. A Non-Hybrid Data-Driven Fuzzy Inference System for Coagulant Dosage in Drinking Water Treatment Plant: Machine-Learning for Accurate Real-Time Prediction. Water, v. 15, n. 6, 2023b, p. 1126.

BRESSANE, A.; MOCHIZUKI, P. S.; CARAM, R. M.; ROVEDA, J. A. F. A system for evaluating the impact of noise pollution on the population's health. Cadernos de saúde pública, 2016, v. 32.

BRESSANE, A.; SPALDING, M.; ZWIRN, D.; LOUREIRO, A. I. S.; BANKOLE, A. O.; NEGRI, R. G.; MORUZZI, R. Fuzzy artificial intelligence—Based model proposal to forecast student performance and retention risk in engineering education: An alternative for handling with small data. Sustainability, v. 14, n. 21, 2022, p. 14071.

BRESSANE, A.; BIAGOLINI, C. H.; MOCHIZUKI, P. S.; ROVEDA, J. A. F.; LOURENÇO, R. W. Fuzzy-based methodological proposal for participatory diagnosis in the linear parks management. Ecological Indicators, v. 80, 2017, p. 153-162.

BRESSANE, A.; BAGATINI, J. A.; BIAGOLINI, C. H.; ROVEDA, J. A. F.; ROVEDA, S. R. M. M.; FENGLER, F. H.; LONGO, R. M. Neuro-fuzzy modeling: a promising alternative for risk analysis in urban afforestation management. Revista Árvore, 2018, v. 42.

BRESSANE, A.; DA SILVA, P. M.; FIORE, F. A.; CARRA, T. A.; EWBANK, H.; DE-CARLI, B. P.; DA MOTA, M. T. Fuzzy-based computational intelligence to support screening decision in environmental impact assessment: A complementary tool for a case-by-case project appraisal. Environmental Impact Assessment Review, v. 85, 2020, p. 106446.

ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.61, n.1, p. 92 – 111, 12/2024
http://dx.doi.org/10.5380/raega.v61i1.95323

CARVALHO MARIA, T. R. B.; BIONDI, D.; BEHLING, A.; DOS REIS, A. R. N.; ZAMPRONI, K.; HO, T. L. Application of artificial intelligence for tree risk assessment optimization in Itanhaém–São Paulo, Brazil. Urban Forestry & Urban Greening, v. 81, 2023, p. 127844.

CHENG, H.; PARK, C. Y.; CHO, M.; PARK, C. Water requirement of Urban Green Infrastructure under climate change. Science of The Total Environment, v. 893, 2023, p. 164887.

CUI, J.; ZHU, M.; LIANG, Y.; QIN, G.; LI, J.; LIU, Y. Land use/land cover change and their driving factors in the Yellow River Basin of Shandong Province based on google earth Engine from 2000 to 2020. ISPRS International Journal of Geo-Information, v. 11, n. 3, 2022, p. 163.

DEMIREL, D. The Impact of Managing Diversity on Building the Smart City A Comparison of Smart City Strategies: Cases from Europe, America, and Asia. SAGE Open, v. 13, n. 3, 2023, p. 21582440231184971.

EWBANK, H.; FRUTUOSO ROVEDA, J. A.; MONTEIRO MASALSKIENE ROVEDA, S. R.; RIBEIRO, A. Ĺ.; BRESSANE, A.; HADI-VENCHEH, A.; WANKE, P. Sustainable resource management in a supply chain: a methodological proposal combining zero-inflated fuzzy time series and clustering techniques. Journal of Enterprise Information Management, v. 33, n. 5, 2020, p. 1059-1076.

FLORES, C. C.; VIKOLAINEN, V.; CROMPVOETS, J. Governance assessment of a blue-green infrastructure project in a small size city in Belgium. The potential of Herentals for a leapfrog to water sensitive. Cities, v. 117, 2021, p. 103331.

GUARIZ, H. R.; GUARIZ, F. R. Avaliação do tamanho e forma de fragmentos florestais por meio de métricas de paisagem para o Município de São Roque do Canaã, Noroeste do Estado do Espírito Santo. Revista Brasileira de Geografia Física, v. 13, n. 05, 2020, p. 2193-2153.

HALDER, B.; BANDYOPADHYAY, J.; AL-HILALI, A. A.; AHMED, A. M.; FALAH, M. W.; ABED, S. A.; YASEEN, Z. M. Assessment of urban green space dynamics influencing the surface urban heat stress using advanced geospatial techniques. Agronomy, v. 12, n. 9, 2022, p. 2129.

HSU, C. C.; SANDFORD, B. A. The Delphi technique: making sense of consensus. Practical assessment, research, and evaluation, v. 12, n. 1, 2019.

JAIN, A.; SHARMA, A. Membership function formulation methods for fuzzy logic systems: A comprehensive review. Journal of Critical Reviews, v. 7, n. 19, 2020, p. 8717-8733.

KARIUKI, R. W.; MUNISHI, L. K.; COURTNEY-MUSTAPHI, C. J.; CAPITANI, C.; SHOEMAKER, A.; LANE, P. J.; MARCHANT, R. Integrating stakeholders' perspectives and spatial modelling to develop scenarios of future land use and land cover change in northern Tanzania. PloS One, v. 16, n. 2, 2021, p. e0245516.

LANGEMEYER, J.; WEDGWOOD, D.; MCPHEARSON, T.; BARÓ, F.; MADSEN, A. L.; BARTON, D. N. Creating urban green infrastructure where it is needed–A spatial ecosystem service-based decision analysis of green roofs in Barcelona. Science of the total environment, v. 707, 2020, p. 135487.

LIMA, C. E. S.; DA SILVA, M. V. M.; ROCHA, S. M. G.; SILVEIRA, C. D. S. Anthropic Changes in Land Use and Land Cover and Their Impacts on the Hydrological Variables of the São Francisco River Basin, Brazil. Sustainability, v. 14, n. 19, 2022, p. 12176.

LIMA, L. Z. B.; DOS SANTOS BATISTA, M.; FERRARETTO, T. R. G.; AUGUSTO, V. F. Pressure-state-response model for assessing environmental impacts in Serra do Japi. Journal of Interdisciplinary Debates, v. 4, n. 03, 2023, p. 119-127.

ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.61, n.1, p. 92 – 111, 12/2024
http://dx.doi.org/10.5380/raega.v61i1.95323

LIN, J.; QIU, S.; TAN, X.; ZHUANG, Y. Measuring the relationship between morphological spatial pattern of green space and urban heat island using machine learning methods. Building and Environment, v. 228, 2023, p. 109910.

LIU, X.; NIU, N.; LIU, X.; JIN, H.; OU, J.; JIAO, L.; LIU, Y. Characterizing mixed-use buildings based on multi-source big data. International Journal of Geographical Information Science, v. 32, n. 4, 2018, p. 738-756.

MASSARO, A.; BIRARDI, G.; MANCA, F.; MARIN, C.; BIRARDI, V.; GIANNONE, D.; GALIANO, A. M. Innovative DSS for intelligent monitoring and urban square design approaches: A case of study. Sustainable Cities and Society, v. 65, 2021, p. 102653.

MOTA, M. T. D.; BRESSANE, A.; ROVEDA, J. A. F.; ROVEDA, S. R. M. M. Classification of successional stages in Atlantic forests: a methodological approach based on a fuzzy expert system. Ciência Florestal, v. 29, 2019, p. 519-530.

NÄSCHEN, K.; DIEKKRÜGER, B.; EVERS, M.; HÖLLERMANN, B.; STEINBACH, S.; THONFELD, F. The impact of land use/land cover change (LULCC) on water resources in a tropical catchment in Tanzania under different climate change scenarios. Sustainability, v. 11, n. 24, 2019, p. 7083.

NASSARY, E. K.; MSOMBA, B. H.; MASELE, W. E.; NDAKI, P. M.; KAHANGWA, C. A. Exploring urban green packages as part of Nature-based Solutions for climate change adaptation measures in rapidly growing cities of the Global South. Journal of Environmental Management, v. 310, 2022, p. 114786.

NIKIFOROVA, A. A.; FLEIS, M. E.; KAZANTSEV, N. N. Multi-scale soil-landscape maps as the basis of geographic information systems for soil melioration. In: IOP Conference Series: Earth and Environmental Science. IOP Publishing, 2019, p. 012038.

OLIVEIRA, J. A. P.; BELLEZONI, R. A.; SHIH, W. Y.; BAYULKEN, B. Innovations in Urban Green and Blue Infrastructure: Tackling local and global challenges in cities. Journal of Cleaner Production, v. 362, 2022, p. 132355.

SILVA, A. L. D.; LONGO, R. M.; BRESSANE, A.; CARVALHO, M. F. H. D. Classification of urban forest fragments based on landscape metrics. Ciência Florestal, v. 29, 2019, p. 1254-1269.

TAVANA, M.; HAJIPOUR, V. A practical review and taxonomy of fuzzy expert systems: methods and applications. Benchmarking: An International Journal, v. 27, n. 1, 2020, p. 81-136.

ZAREI, F.; NIK-BAKHT, M. Citizen engagement body of knowledge–A fuzzy decision maker for index-term selection in built environment projects. Cities, v. 112, 2021, p. 103137.

ZHANG, D.; PEE, L. G.; PAN, S. L.; CUI, L. Big data analytics, resource orchestration, and digital sustainability: A case study of smart city development. Government information quarterly, v. 39, n. 1, 2022, p. 101626.

ZHENG, F.; XIAO, C.; FENG, Z. Impact of armed conflict on land use and land cover changes in global border areas. Land Degradation & Development, v. 34, n. 3, 2023, p. 873-884.

ZHOU, G.; PAN, Q.; YUE, T.; WANG, Q.; SHA, H.; HUANG, S.; LIU, X. Vector and Raster Data Storage based on Morton Code. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, v. 42, 2018, p. 2523-2526.

ZHU, H.; SHEN, LIYIN; REN, Y. How can smart city shape a happier life? The mechanism for developing a Happiness Driven Smart City. Sustainable cities and society, v. 80, 2022, p. 103791.

O ESPAÇO GEOGRÁFICO EM ANÁLISE
https://revistas.ufpr.br/raega
ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.61, n.1, p. 92 – 111, 12/2024
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