

UNIVERSIDADE FEDERAL DE SÃO CARLOS
CENTRO DE CIÊNCIAS E TECNOLOGIAS PARA A SUSTENTABILIDADE (CCTS)
PROGRAMA DE PÓS-GRADUAÇÃO EM PLANEJAMENTO E USO DE RECURSOS
RENOVÁVEIS (PPGPUR)

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Urban Landscape Resilience: Integrating Natural Areas with Urban Planning

Sorocaba

2025

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Urban Landscape Resilience: Integrating Natural Areas with Urban Planning

Trabalho de Conclusão de Tese apresentado ao Programa de Pós-Graduação em Planejamento e Uso de Recursos Renováveis para obtenção do título de Doutora em Planejamento e Uso de Recursos Renováveis da Universidade Federal de São Carlos. Área de concentração: Produção sustentável.

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Financiamentos: Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) Processo: 88887.603853/2021-00 e Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) Processos: 2021/04421-7 e 2023/00014-3.

Sorocaba

2025

Marina Pannunzio, Ribeiro

Urban landscape resilience: integrating natural areas with urban planning / Ribeiro Marina Pannunzio -- 2025. 147f.

Tese de Doutorado - Universidade Federal de São Carlos, campus Sorocaba, Sorocaba

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Bibliografia

1. Multicriteria evaluation. 2. Urban ecosystem services. 3. Green infrastructure. I. Marina Pannunzio, Ribeiro. II. Título.

Ficha catalográfica desenvolvida pela Secretaria Geral de Informática (SIn)

DADOS FORNECIDOS PELO AUTOR

Bibliotecário responsável: Maria Aparecida de Lourdes Mariano - CRB/8 6979



UNIVERSIDADE FEDERAL DE SÃO CARLOS

Centro de Ciências e Tecnologias Para a Sustentabilidade
Programa de Pós-Graduação em Planejamento e Uso de Recursos Renováveis

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O Relatório de Defesa assinado pelos membros da Comissão Julgadora encontra-se arquivado junto ao Programa de Pós-Graduação em Planejamento e Uso de Recursos Renováveis.



A história de Maria - motivações do projeto "Resiliência da Paisagem Urbana: Integração de Áreas Naturais com o Planejamento Urbano"

A história de Maria e sua família é marcada por uma mudança para uma grande cidade no interior de São Paulo, impulsionada pela busca por uma vida melhor. No entanto, a dura realidade dos alugueis altos os força a se estabelecer em áreas periféricas com problemas socioambientais.

Maria, trabalhando como babá em um bairro privilegiado, contrasta a realidade de sua família com a opulência da casa dos patrões e o acesso a um belo parque do bairro.

A virada ocorre quando o terreno sujo e abandonado, em frente à casa de Maria é transformado em um parque. Com esperança renovada, ela acompanha entusiasticamente a construção, compartilhando novidades com os vizinhos e promovendo a criação de uma associação do bairro. Maria lidera a iniciativa de um projeto de agricultura urbana sugerido pelo engenheiro da prefeitura. No dia da inauguração, Maria celebra radiante. Agora, sua família e comunidade têm um parque tão bonito quanto o bairro "chique" da patroa, proporcionando não apenas um local de lazer, mas também a visita de alguns pássaros que voltaram a aparecer. Agora Maria pode ouvir o canto de um pássaro que a lembra da infância no sítio onde morava.

A história fictícia reflete a realidade de muitas famílias brasileiras que migram para centros urbanos em busca de melhores condições de vida, mas acabam em áreas periféricas insalubres, alagadiças, muito íngremes e altamente adensadas nas franjas urbanas.

Será que o planejamento da infraestrutura verde nas cidades pode proporcionar múltiplos benefícios sociais e ecológicos, tais como a entrega de serviços físicos e emocionais benéficos para a saúde humana, e principalmente para as pessoas que vivem em situação de vulnerabilidade social como a de Maria?

Essa é uma das perguntas abordadas pelo projeto "Resiliência da Paisagem Urbana: Integração de Áreas Naturais com o Planejamento Urbano", que foi desenvolvido com financiamentos da CAPES e FAPESP na UFSCar Sorocaba e na Queen's University no Canadá.

Financiamentos: CAPES: 88887.603853/2021-00 e FAPESP: 2021/04421-7 e 2023/00014-3.

O CRESCIMENTO URBANO

e o aumento da temperatura



Proposta para um desenvolvimento urbano que colabora com o meio ambiente e a sociedade.

COMO A EXPANSÃO DAS ÁREAS URBANAS CONTRIBUI COM O AUMENTO DE TEMPERATURA



PERIURBANIZAÇÃO

É o fenômeno que descreve a transição de áreas rurais para zonas urbanas, caracterizando-se pela transformação gradual do ambiente e das atividades econômicas;



CANALIZAÇÃO DOS CURSOS DE ÁGUA

Gera o aumento da temperatura, a partir da alteração do equilíbrio térmico;



ALTERAÇÃO DA SUPERFÍCIE

Materiais de construção, como concreto, asfalto, e outros materiais absorventes de calor, tornam a superfície da terra impermeável, alterando o equilíbrio natural da energia;

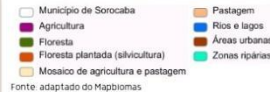
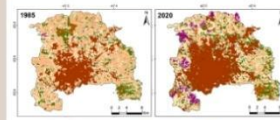


ILHAS DE CALOR URBANAS

Fenômeno causado pela emissão de gases do efeito estufa, combinado com superfícies impermeáveis, resultando em um aumento da calor dentro da cidade.

O HISTÓRICO DO PROBLEMA NA CIDADE DE SOROCABA

A análise temporal dos dados de uso e cobertura da terra revelou um aumento de 64,75% na área urbana desde 1985. Sorocaba se tornou predominantemente urbana em 2015, com mais de 30% de áreas urbanizadas. Historicamente, a expansão urbana explorou e converteu terras agrícolas no município de Sorocaba, movimento conhecido como "periurbanização".



Fonte adaptado do Mapbiomas

O IMPACTO CAUSADO NA POPULAÇÃO



Segregação socioeconômica, impulsionada por um sistema dependente de automóveis;



Efeitos prejudiciais na saúde decorrentes do aumento da poluição e do sedentarismo.

PROPOSTAS DE SOLUÇÃO

- Planejamento urbano compacto;
- Terras agrícolas protegidas em torno das cidades;
- Maior disponibilidade de infraestruturas verdes em áreas urbanas e periurbanas;



- Criação de Unidades de Conservação (UCs);
- Incentivos para a conservação de remanescentes florestais periurbanos;
- Agricultura urbana em espaços públicos e terrenos baldios;

- Arborização urbana;
- Combinação de infraestrutura verde com infraestrutura de engenharia tradicional;
- Restauração de campos antrópicos e zonas ripárias;



Referência: Ribeiro, M.P., Menezes, G.P., Figueiredo, G.K.D.A., de Mello, K., Valente, R.A., 2024. **Impacts of urban landscape pattern changes on land surface temperature in Southeast Brazil**. Remote Sensing Applications: Society and Environment 101142. <https://doi.org/10.1016/j.rsase.2024.101142>.

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Link access: 10.5281/zenodo.13987508 (DOI)

ACKNOWLEDGMENTS

First and foremost, I want to express my gratitude to the Coordination for the Improvement of Higher Education Personnel (CAPES, No. 88887.603853/2021-00) and the São Paulo Research Foundation (FAPESP, Nos. 2021/04421-7 and 2023/00014-3) for their support of this thesis.

I want to express my heartfelt gratitude to my advisors, Roberta and Kaline, for teaching me so much and their dedication throughout my journey. Your guidance has been invaluable.

To my lovely family, Juca and Rosa, thank you for your unwavering love and support during this crucial phase of my life - your steadfast encouragement has meant everything to me.

I want to thank my Canadian advisor, Dongmei Chen, for warmly welcoming me and embracing me in her lab. I am deeply grateful to my lab mates, Masoud and his wife Rayhane, Mario (my dear Jingheng), Saba, Bo, and Seun, for making me feel cherished and supported.

To my Brazilian family in Kingston, you are incredible friends who have supported me with love, hugs, and affection - I love you all. Your kindness and companionship have been a source of strength and joy throughout this journey.

To my dear friend Ana Paola, who rescued me during a challenging moment, I have so much love for you. To my dear friend Fabiana, thank you for your companionship, shared adventures, and invaluable partnership. To my Brazilian lab mates Daniele, Daniel, Maria Inês, Carla, and Barbara, thank you for your support, kindness, and dedication.

To my professors, Franciane, Marcos, and Marcel, I appreciate your insightful guidance, inspiring words, and support. Your encouragement has kept me moving forward.

To Luciana from the administrative office, I sincerely appreciate your attentiveness and assistance. To Fabiana, my psychological support at UFSCar, thank you for listening and being there for me during this challenging time.

Indeed, a thesis is never built alone - I have relied on much help and support. I want to thank everyone who offered me words of encouragement, pieces of advice, smiles, and abundant love. This journey has been filled with exchanges of knowledge, experiences, and life lessons that have transformed me and propelled me forward in creating the work I truly believe in.

I hope this research can someday help improve people's lives, particularly those who suffer most from inadequate urban planning, urban segregation, and, most importantly, the climate changes that affect us all—the Brazilian people.

Long live the Brazilian public university!

RESUMO

RIBEIRO, Marina Pannunzio. Resiliência da Paisagem Urbana: Integração das Áreas Naturais com o Planejamento Urbano. 2025. Tese (Doutorado em Planejamento e Uso de Recursos Renováveis) – Universidade Federal de São Carlos, Sorocaba, 2025.

Com a rápida intensificação da urbanização, as projeções indicam que até 2050, quatro em cada cinco pessoas residirão em cidades, ressaltando a necessidade urgente de mitigar os impactos ambientais e, ao mesmo tempo, promover o desenvolvimento urbano sustentável. As cidades, que respondem por cerca de 70% das emissões globais de gases de efeito estufa, são ao mesmo tempo vulneráveis às mudanças climáticas e fundamentais para enfrentá-las. Desastres recentes relacionados ao clima, como inundações e ondas de calor, exacerbam as desigualdades socioeconômicas, afetando desproporcionalmente as populações vulneráveis. Enfrentar esses desafios requer soluções integradas que promovam o crescimento urbano verde, inclusivo e resiliente. A infraestrutura verde, uma solução baseada na natureza, surgiu como uma estratégia fundamental para aumentar a resiliência climática das cidades, ao mesmo tempo em que fornece diversos benefícios sociais, ecológicos e econômicos. Esta tese explora o planejamento da infraestrutura verde para otimização de serviços ecossistêmicos e benefícios à comunidade urbana. Usando o município de Sorocaba como estudo de caso, o objetivo principal foi desenvolver um modelo espacial para identificar áreas prioritárias para a implementação de infraestrutura verde, abordando temas como biodiversidade, mitigação de enchentes, regulação de temperatura e bem-estar social. Além disso, a tese teve como objetivo explorar simulações de cenários de planejamento urbano, examinando futuros plausíveis para 2030 e 2050. A hipótese de pesquisa postula que a modelagem espacial pode identificar áreas prioritárias integrando sistemas naturais e sociais dentro das complexidades dos ambientes urbanos. Os resultados destacam compensações espaciais e sinergias na identificação de áreas prioritárias para multisserviços ecossistêmicos urbanos, enfatizando a importância de uma rede bem conectada de infraestrutura verde para aumentar a sua multifuncionalidade e promover o acesso equitativo a espaços verdes, especialmente em áreas com desigualdades socioespaciais. A pesquisa também analisou cenários futuros de crescimento urbano, evidenciando como o planejamento urbano compacto pode mitigar os efeitos negativos da expansão desordenada e fortalecer a resiliência urbana, promovendo sustentabilidade, inclusão e justiça ambiental.

Palavras-chave: Avaliação multicriterial; Serviços ecossistêmicos urbanos; Infraestrutura verde; Cenários futuros.

ABSTRACT

RIBEIRO, Marina Pannunzio. Urban Landscape Resilience: Integrating Natural Areas with Urban Planning. 2025. Thesis (PhD in Planning and Use of Renewable Resources) – Federal University of São Carlos, Sorocaba, 2025.

As urbanization accelerates rapidly, projections indicate that by 2050, four out of every five people will live in cities, underscoring the urgent need to mitigate environmental impacts while promoting sustainable urban development. Cities, responsible for around 70% of global greenhouse gas emissions, are both vulnerable to climate change and essential to addressing it. Recent climate-related disasters, such as floods and heatwaves, exacerbate socioeconomic inequalities, disproportionately impacting vulnerable populations. Confronting these challenges necessitates integrated solutions encouraging green, inclusive, and resilient urban growth. Green infrastructure, a nature-based solution, has emerged as a key strategy for enhancing cities' climate resilience while delivering multiple social, ecological, and economic benefits. This thesis investigates green infrastructure planning to optimize ecosystem services and its benefits for urban communities. Using the municipality of Sorocaba as a case study, the main objective was to develop a spatial model to identify priority areas for implementing green infrastructure, addressing themes like biodiversity, flood mitigation, temperature regulation, and social wellbeing. Additionally, the thesis aimed to explore urban planning scenario simulations, examining plausible futures for 2030 and 2050. The research hypothesis posits that spatial modeling can pinpoint priority areas by integrating natural and social systems amid the complexities of urban environments. The results highlight spatial trade-offs and synergies in identifying priority areas for urban multi-ecosystem services, emphasizing the importance of a well-connected green infrastructure network to enhance its multifunctionality and promote equitable access to green spaces, especially in areas with socio-spatial inequalities. The research also analyzed future urban growth scenarios, demonstrating how compact urban planning can mitigate the negative effects of unchecked sprawl and strengthen urban resilience, promoting sustainability, inclusion, and environmental justice.

Keywords: Multicriteria evaluation; Urban ecosystem services; Green infrastructure; Future scenarios.

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1 INTRODUCTION

As the global population becomes increasingly urbanized, and projections indicate that by 2050, four out of five people will live in cities, there is an urgent need to mitigate the environmental impacts of urbanization while promoting more sustainable and livable urban spaces (Childers *et al.*, 2019; Meerow, 2020; UN-Habitat, 2024). Data from the most recent report by the Intergovernmental Panel on Climate Change (IPCC) indicate that cities produce around 70% of the total greenhouse gas emissions that raise the planet's temperature (IPCC, 2022). Despite their large carbon footprint and being particularly vulnerable to the effects of global warming, cities can also be key spaces for adapting to and mitigating climate change (Dodman *et al.*, 2022).

On the brink of irreversible collapse, cities face critical situations that require urgent responses (Ripple *et al.*, 2024). The recent floods that devastated southern Brazil in May are a stark reminder of the urgency to address climate change. The disaster claimed 213 lives, affected 2.4 million people, displaced 600,000, and caused extensive damage to both urban and rural infrastructure (Pillar and Overbeck, 2024). Simultaneously, the increasing frequency and intensity of heatwaves have emerged as a critical global public health challenge (Geirinhas *et al.*, 2021; Domeisen *et al.*, 2022).

In Brazil, these events have exacerbated socioeconomic inequalities, further amplifying their impact on vulnerable populations (Monteiro Dos Santos *et al.*, 2024). Pre-existing inequalities and development challenges, such as poverty and a lack of access to essential services, such as access to clean water, increase vulnerability to climate events and undermine the ability of these vulnerable communities to adapt (Brazilian Black Movement, 2022; Schipper *et al.*, 2022).

Integrated solutions that address urban development and social inequality while mitigating climate change and preventing biodiversity loss can help cities foster green, competitive, and low-carbon growth and develop resilient, inclusive, and livable societies (World Bank Group, 2019). To meet emerging challenges, the new urban narrative or the "Global Urban Agenda" must integrate climate change, health and wellbeing, and biodiversity agendas to ensure the resilience of urban infrastructure (UN and WHO, 2020; Keith, D. A. *et al.*, 2022; CBD, 2023; Schröter *et al.*, 2023; UN-Habitat, 2024).

Today, the concept of a "Global Urban Agenda" has taken center stage, reflecting the growing recognition of cities as critical players in addressing global challenges (Keith, M. *et al.*, 2022). Over the past decade, efforts to position cities at the forefront of international

priorities have gained significant momentum. These efforts culminated in the adoption of Sustainable Development Goal (SDG) 11, which aims to "Make cities and human settlements inclusive, safe, resilient, and sustainable" (UN, 2015). The Paris Agreement similarly acknowledges the pivotal role of cities in combating climate change (Keith, M. *et al.*, 2022; UN, 2017). Reinforcing this perspective, the IPCC synthesis report emphasizes, with high confidence, that urban systems are essential for reducing emissions and advancing climate-resilient development (Schipper *et al.*, 2022). Furthermore, the post-2020 biodiversity framework underscores the importance of enhancing urban commitments to address biodiversity loss (CBD, 2023).

Several mitigation options are technically viable, increasingly cost-effective, and broadly supported by the public (IPCC, 2023). These include solar and wind energy, the electrification of urban systems, urban green infrastructure, energy efficiency improvements, demand-side management, better management of forests, crops, and grasslands, as well as efforts to reduce food waste and loss (IPCC, 2023).

This new narrative comes to this thesis through green infrastructure. This nature-based solution (NbS) approach uses biodiversity and ecosystem services to help people adapt to the impacts of climate change (Manes *et al.*, 2022). Green infrastructure is widely promoted for its diverse social, ecological, and technical benefits, ranging from enhanced public health to effective stormwater management (Mansur *et al.*, 2022). For instance, green infrastructure designed to increase resilience against flooding can also improve food security, provide public green spaces, and deliver economic benefits (Adegun, 2017). Additionally, such infrastructure not only shields vulnerable communities from climate change impacts but is also cost-effective and strongly aligned with the SDGs (Griscom, 2022).

Research Question

In this manner, this thesis aimed to answer whether green infrastructure planning in cities could provide multiple social and ecological benefits, such as delivering physical and emotional services that benefit human health, especially for people living in situations of social vulnerability.

Research hypothesis

This thesis is based on the hypothesis that a spatial model can be developed to identify priority areas for expanding green infrastructure in cities to optimize multiple ecosystem

services. This approach considers the interconnections between natural and social systems and the challenges of the extensively built urban environment.

Objectives

Main Objective:

The main objective of this thesis was to create a spatial model to support decision-making in identifying priority areas for implementing green infrastructure to enhance multiple ecosystem services in cities. Additionally, the thesis aimed to explore scenario simulations, examining plausible futures through urban planning, using the municipality of Sorocaba as a case study.

Specific objectives:

- Comprehending the concept of green infrastructure;
- Generate four green infrastructure spatial planning model maps, which separately address the following priority themes: biodiversity, flood mitigation, temperature mitigation, and social wellbeing;
- Generate a single map of green infrastructure spatial planning model map, considering the four priority themes;
- Evaluate the final mapping of priority areas in conjunction with territorial public policies;
- Make a forecast for urban area sprawl (2030 – 2050);
- Compare urban sprawl scenarios for 2030 and 2050, by assessing the "business-as-usual" (BAU) scenario, which reflects current development trends, alongside the "ecosystem services conservation" (ESC) scenario, which prioritizes integrating key areas to enhance green infrastructure in urban centers.

Thesis structure

The present thesis consists of one literature review chapter (Chapter 2), six chapters presenting thesis results (Chapters 3-7), and a final consideration chapter (Chapter 8). The six chapters presenting the thesis results are as follows:

Chapter 2, titled “Urban Green Infrastructure: A Latin American Strategy?” presents a literature review on the application of green infrastructure in Latin America. Originally

published in Portuguese as a book chapter, it has been translated for inclusion in this thesis (Ribeiro *et al.*, 2023).

Chapter 3, titled “Impacts of Urban Landscape Pattern Changes on Land Surface Temperature in Southeast Brazil,” presents a spatio-temporal analysis of land use and land cover changes in Sorocaba over the past 36 years, alongside their effects on land surface temperature. These results were essential to the thesis as they provided a comprehensive understanding of the impact of urbanization on thermal dynamics, offering knowledge for sustainable urban planning and climate adaptation strategies. This study was published in *Remote Sensing Applications: Society and Environment* journal in January 2024 (Ribeiro, Menezes, *et al.*, 2024).

Chapter 4, titled “Prioritization of New Green Infrastructures Aimed at Protecting Urban Biodiversity,” focused on developing a geospatial model to support decision-making in identifying priority areas for expanding green infrastructure to enhance biodiversity conservation in urban landscapes, with an emphasis on the Atlantic Forest Biome. This study presented our first spatial model results, utilizing a Multicriteria Evaluation at the city scale to determine priority areas for conservation and restoration. This work was presented at the *2024 IEEE International Geoscience and Remote Sensing Symposium in Athens, Greece*, in July 2024 and published in the conference proceedings (Ribeiro, Mello, *et al.*, 2024)

Chapter 5, “Resilience of Urban Landscapes: Identifying Priority Areas for Green Infrastructure through Multicriteria Evaluation”, aims to develop a city-scale decision-support model called the Priority Areas for Green Infrastructure (PAGI) for planning priority areas that enhance four urban ecosystem services: biodiversity, flood mitigation, heat mitigation, and social wellbeing. This model integrates mixed approaches, such as Multicriteria Evaluation, literature review, and participatory technique. This article is intended for submission to the international “*Landscape and Urban Planning*”.

Chapter 6, titled “Land Use/Land Cover Forecast and Urban Sprawl Analysis in a Brazilian City within the Atlantic Forest Biome,” presents our initial results on future urban land use changes using geospatial techniques and a Cellular Automata model to simulate scenarios for 2050. Structural landscape metrics were applied to quantify and characterize the projected changes. This study was presented at the *ISPRS Midterm Symposia 2024* in Belém, Pará, Brazil, in November 2024 and was published in the conference proceedings (Ribeiro, Viégas, *et al.*, 2024).

Finally, Chapter 7, titled “Urban Growth Scenarios: Evaluating Compact and Green City Strategies Versus Business-as-Usual Using Landscape Metrics,” utilizes geospatial

technique, cellular automata algorithms, and structural metrics to simulate and evaluate urban expansion under two contrasting scenarios. The first, the "business-as-usual" (BAU) scenario, reflects current development trends, while the second, the "ecosystem services conservation" (ESC) scenario, emphasizes the integration of priority areas to enhance green infrastructure in urban centers. This article is intended for submission to the international journal "*Urban Ecosystems*".

2 URBAN GREEN INFRASTRUCTURE: LATIN AMERICAN STRATEGY?

Abstract

Socially just climate change adaptation actions and building resilience through green infrastructure have been incorporated into urban planning and decision-making in cities worldwide. Green infrastructure is a strategy known as a nature-based solution for adapting cities to climate change. It is based on maximizing the benefits that nature provides to people through ecosystem services. The objective of this work was a literature review on the use of green infrastructure to adapt cities to climate change and increase urban resilience, mainly in Latin American cities. Our results can support planning actions to help cities achieve the objectives of the United Nations campaign - Race for Resilience - achieving healthier, cleaner, safer, and more resilient cities to the impacts of climate change.

Keywords: Urban planning, climate change, nature-based solutions, literature review.

2.1 INTRODUCTION

Urban areas could triple between 2015 and 2050 to meet global population growth, which will be greatest in developing regions such as Latin American countries (IPCC, 2022a). The expansion of urban land contributes to the degradation of forests and other natural areas and occurs mainly on agricultural land or pastures in peripheral regions of the city (Chen *et al.*, 2020). These changes in land use and coverage have consequences for the urban environment, such as the impact on biodiversity conservation, the water, carbon, aerosol, and nitrogen cycles, and the climate system at local and global scales (Vitousek *et al.*, 1997; McDonald *et al.*, 2008; Seto and Shepherd, 2009; IPCC, 2018). Cities and communities struggle to find a strategic balance between urbanization and the conservation of natural areas. In this sense, green infrastructure is an emerging trend driving a resilient urban environment (Herzog and Rosa, 2010).

Urban green infrastructure can be understood as an interconnected network of natural and semi-natural green spaces that have multiple social and ecological benefits, including improved public health, flood mitigation, improved air and water quality, carbon storage, and habitat and species conservation, as well as thermal comfort and urban affective belonging (Pennino *et al.*, 2016; Childers *et al.*, 2019; Teixeira and de Carvalho Martins, 2020). Cities

worldwide are actively promoting the expansion of their green infrastructure to mitigate climate change and increase urban resilience (IPCC, 2022a).

Studies in major global urban centers such as Detroit, New York, Los Angeles, Manila, and Toronto have proposed plans to expand these areas on a large scale (Meerow and Newell, 2017; Green Analytics Corp., 2018; Hölscher *et al.*, 2019; Meerow, 2019, 2020). Since 2013, the European Commission has adopted a series of strategies to tackle the problem of pollution and improve people's quality of life in large cities by promoting green infrastructure, both in rural (peri-urban) areas and in the urban environment (European Commission, 2015). In Latin American cities, especially those in tropical regions - with high humidity and hot temperatures all year round - green infrastructure is undoubtedly a solution that can improve the resilience of the urban ecosystem to climate change challenges (Manoli *et al.*, 2019; Wilson *et al.*, 2022).

In this context, assuming green infrastructure as a highly relevant field of research, this article aimed to review the literature on the use of green infrastructure to adapt cities to climate change and increase urban resilience, mainly in Latin American cities, to understand the scientific framework on the use of green infrastructure as a global infrastructure resource against climate change.

2.2 MATERIAL AND METHODS

We focused on academic publications in English from the Web of Knowledge database, selecting studies related to green infrastructure, green areas, climate change, resilience, and urban, for the entire period available until December 2022.

To analyze the retrieved articles, we conducted a descriptive analysis using VOSviewer (Eck, van and Waltman, 2014) and Excel. VOSviewer, a tool designed for mapping and exploring network data, was specifically used to identify the countries that contributed the most to research on these topics.

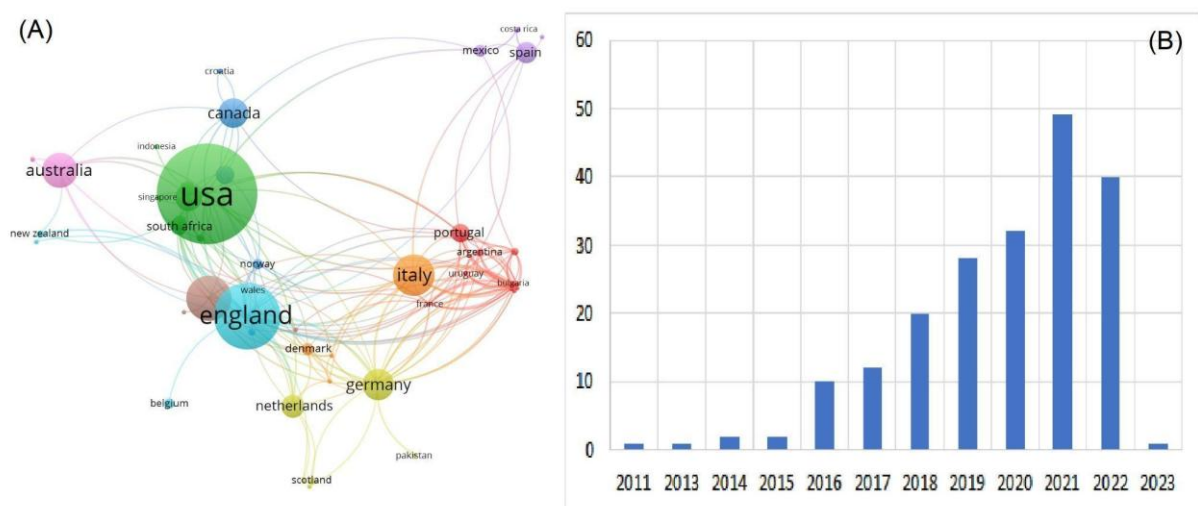
2.3 RESULTS AND DISCUSSION

We found 198 articles related to the terms green infrastructure, green areas, climate changes, resilience, and urban, with the countries that published the most on the topic being the United States (25.8%), England (16.2%), China (10.6%), Italy (9.6%), Australia (8.1%) and Canada (6.6%) (Figure 2.1A). While rich countries such as the United States and England lead research on these topics, with 51 and 32 publications, respectively, few publications appear in

Latin American countries, such as Mexico (5), Brazil (3), Argentina (3), Chile (2), Uruguay (2), and Costa Rica (1). Most urban scientists and resources are concentrated in the global north. Still, the most critical urban concerns are in cities in the global south (McPhearson *et al.*, 2016; Palme, 2021), specifically Latin American cities, which are highly exposed, vulnerable, and heavily impacted by climate change (IPCC, 2022b). Therefore, academic research and the involvement of national and local governments are fundamental in leading efforts to adapt Brazilian cities to climate change.

We must respond to the failure of existing Brazilian urban development models, which grew cities without urban and territorial planning and with extreme territorial inequality (Keith *et al.*, 2022). These responses must be through a paradigm shift, prioritizing natural areas, green-blue infrastructure projects, and proposing the conservation of urban and peri-urban agriculture and urban afforestation (Pasimeni *et al.*, 2019; Rędzińska and Piotrkowska, 2020; Lucertini and Di Giustino, 2021). The use of green infrastructure as an ecosystem service is still very recent (Figure 2.1B). Still, studies show that it will help cities become more resilient to the socio-environmental problems they will face more frequently and intensely (IPCC, 2022a).

Figure 2.1 Network visualization of the countries that published the most on the topics: green infrastructure, green areas, climate changes, resilience, and urban areas between 2011 and 2023 (A) and publication graph (B).



Source: prepared by the author.

Publications on these topics began in 2011 and stood out in 2021 during the Covid-19 pandemic (Figure 2.1B). The pandemic has forced society to look at cities differently, and public spaces such as squares and urban parks have become increasingly used by urban

residents. The world is turning to cities, and researchers and society in general are rethinking urban space, not only from a health perspective but also from an ecological perspective (UN-Habitat, 2021). Our results show that there has been an intensification of efforts to understand the role of green infrastructure in urban areas, resulting in research that reflects its use as an important ecosystem service and ensures essential benefits, such as improved water quality and flood control, air pollution control, mitigation of heat islands, reduced mortality from extreme risks (heat and floods), food security through urban agriculture, ecological equity, increased biodiversity, and of course, urban resilience and sustainability (Table 2.1).

Table 2.1 Relationship between types of green infrastructure and their multiple ecosystem benefits and researched references.

Green infrastructure	Ecosystem benefits	References
Urban and peri-urban agriculture	It contributes to food security, improves soil physical characteristics, boosts biodiversity and pollination, fosters a sense of community belonging, and optimizes water infiltration, helping to mitigate floods.	(Corrêa <i>et al.</i> , 2021; Green Analytics Corp., 2018; Lucertini and Di Giustino, 2021)
Green roofs, rain gardens, wetlands for rainwater storage, and permeable pavements.	It increases resilience to urban flooding and improvements in urban microclimate.	(Li <i>et al.</i> , 2019; Newman <i>et al.</i> , 2022)
Riparian zones - Green-blue infrastructure	It improves water quality and rainwater storage capacity, reducing the effects of flooding and increasing biodiversity.	(Gašparović <i>et al.</i> , 2022; Park <i>et al.</i> , 2020)
Conventional grey infrastructures combined with green infrastructures	It contributes to bio-infiltration and underground storage of rainwater.	(Dong <i>et al.</i> , 2017; Moore <i>et al.</i> , 2016)
Parks and urban green areas	It contributes to temperature regulation, stormwater runoff mitigation, air quality improvement, biodiversity, recreation, scenic beauty, and environmental justice.	(Choi and Kim, 2022; Herreros-Cantis and McPhearson, 2021)
Urban and peri-urban agriculture and urban afforestation	It mitigates urban heat islands, increases biodiversity, and supports pollinators.	(Anderson <i>et al.</i> , 2022; Coutts and Hahn, 2015; Di Leo <i>et al.</i> , 2016; Lin <i>et al.</i> , 2015)

Dense vegetation (urban forest)	It contributes to urban heat island mitigation, biodiversity, and stormwater runoff mitigation.	(Anderson <i>et al.</i> , 2022; Cotlier and Jimenez, 2022; Zzaman <i>et al.</i> , 2021)
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Source: prepared by the author.

Recent changes in how science analyzes complex systems involving natural environments and humans have opened opportunities to develop holistic land use design, planning, and management models (Mosler and Hobson, 2021). The results demonstrate that the location of green infrastructure requires a holistic understanding of the political, social, economic, and environmental aspects of the urban ecosystem. This involves the physical and human parts of the environment to be studied, in addition to the cooperation and participation of stakeholders to ensure the initiative's success (Tauhid and Zawani, 2018). An integrated approach combining participatory planning - engaging society, urban planners, and policymakers - along with strong institutional support and multicriteria evaluation methods, is essential for achieving socially equitable and climate-resilient urban development (Sturiale and Scuderi, 2019; Choi *et al.*, 2021).

The research findings emphasize the urgent need to address climate change starting in cities, where most of the global population resides. These efforts should be integrated with urban land use governance to advance environmental justice (UN-Habitat, 2021). Environmental justice, promoted by green infrastructure through the improvement of urban ecosystem regulation services, can have a substantial impact on the health of the urban population (UN-Habitat, 2020) and has been proposed by several international organizations, such as the United Nations campaign - Race to Resilience (<https://climatechampions.unfccc.int/>), which promotes the development of healthier, cleaner, safer, more resilient cities with more significant equity in tackling the impacts of climate change.

2.4 CONCLUSION

Seeking to understand the scientific framework for using green infrastructure as a global infrastructural resource against climate change, we observed that the holistic global vision for using this infrastructure to combat climate change and increase urban resilience is, above all, recent. Furthermore, the rich countries of the global North concentrate the majority of academic

research, while the countries of the global South, especially those that makeup Latin America, are highly vulnerable to climate change.

Despite the recent use of green infrastructure as a resource to combat climate change, several studies have demonstrated its multifunctionality and importance. Green infrastructure can be understood as urban and peri-urban agriculture, green roofs and wetlands for water storage, rain gardens, as well as permeable pavements, including riparian zones and urban parks and squares, urban afforestation, and dense vegetation. Each has its own specificity and provides one or more ecosystem services. Their location is of utmost importance for the urban ecosystem, which can help achieve equity and environmental justice for all urban residents.

Finally, our results demonstrate the strong call for cities to adapt and become resilient to face climate change, which is current and not future. In this sense, we emphasize that the results of this review can support information on land use management, remediation, and adaptation of cities to climate change, as well as increasing urban resilience and helping cities achieve the goals of the United Nations campaign - Race to Resilience.

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3 IMPACTS OF URBAN LANDSCAPE PATTERN CHANGES ON LAND SURFACE TEMPERATURE IN SOUTHEAST BRAZIL

Abstract

Urban sprawl is a global concern, considering the current climate change scenario. The conversion of natural habitats or other land uses to urban areas increases the Land Surface Temperature (LST), impacting people mainly in tropical regions, such as Brazil, where the temperature is aggravated by high air humidity. In this context, we assessed the seasonal variation of LST in response to the land-use/land-cover (LULC) changes over a large city in southwest Brazil during the last 36 years (1985-2020). We used Mapbiomas LULC data and LST retrieved from the Landsat series with the Google Earth Engine platform. The methodology involved the change detection analysis from 1985 to 2020 for all LULC types, a non-parametric Dwass-Steel-Critchlow-Fligner test to estimate the LST spatio-temporal variability over different LULC types, and a non-parametric Sperman's rho test and scatter plots to relate LST changes to the LULC patterns. The results presented areas exchanging under an intense urbanization process, wherein nearly 13% of the transitions were from agricultural to urban areas. These transitions occurred jointly with an increase in temperature for all LULC types. Forest formation registered the lowest LST and a moderate to strong negative correlation with LST in both seasons. On the other hand, urban areas showed the highest temperatures and a moderate to strong positive correlation with LST in summer. From 1985 to 2020, the mean temperature in urban (built-up) areas during the summer increased by 7°C. In 2020, the mean temperature in urban areas was 32.5°C and 27.8°C in forested areas during the summer. The main contribution of this study is to provide evidence-based support for establishing LULC governance at the city scale. It offers essential scientific information about the detrimental impact of urban sprawl against the climate benefits of green infrastructure on the city scale, even in tropical regions with high forest fragmentation, temperatures, and long periods with high air humidity.

Keywords: Climate change, Impervious surface, Google earth engine, Extreme heat, Atlantic Forest biome.

3.1 INTRODUCTION

We live in the urban century, with 2.4 billion more people expected in cities by 2050, i.e., two-thirds of the world population (Elmqvist *et al.*, 2019; United Nations, 2021). The increase in urban population drives the development of new infrastructure, such as road construction, houses, buildings, water, sanitation, energy, and transport (Mahtta *et al.*, 2019; Seto *et al.*, 2012), and even if urban areas represent a small part of the world's land (nearly 2%) (UN-Habitat, 2020), the urbanization is considered one of the most long-lasting and impactful land-use/land-cover (LULC) changes (Bounoua *et al.*, 2015; Shepherd *et al.*, 2013). Urban construction materials, generally made of concrete, asphalt, and other heat-absorbing materials, make the earth's surface impervious, changing the natural balance of energy and causing long-term changes in radiative, thermal, and aerodynamic fluxes (Crippa *et al.*, 2021; IPCC, 2018; Peres *et al.*, 2018). Urbanization has consequences such as an increase in both air and the land surface temperature (LST), which can unleash many welfare problems for the urban population, mainly affecting the population's health in tropical regions such as Brazil (Diniz *et al.*, 2020; Miranda *et al.*, 2022).

The LST can be obtained by remote sensing techniques through satellite sensors and has been applied in many environmental studies, such as vegetation monitoring, disaster management, fires monitoring, soils, geology, and Urban Heat Island (UHI) (Ibrahim and Abu-Mallouh, 2018; Sayão *et al.*, 2020; Jamali *et al.*, 2022; Liao *et al.*, 2022; Stoyanova *et al.*, 2022). The LST can be defined as the radiative earth temperature, which can vary with LULC change, influenced by factors such as land surface conditions, surface reflective properties (albedo), the presence or not of green areas, atmospheric water vapor, and latent and sensible heat fluxes (Voogt and Oke, 2003; Bright *et al.*, 2017; Duveiller *et al.*, 2018). It is predicted that urban LULC changes, such as the loss of green area cover - one of the most common consequences of urban development - together with climatic changes, can influence LST, increase the thermal discomfort level, and consequently, heat stress among all living beings (IPCC, 2018, 2019).

In Brazil, the Atlantic Forest Biome concentrates nearly 60% of the Brazilian population (Scarano and Ceotto, 2015; SOS Mata Atlântica, 2019) and is one of the most vulnerable hotspots to climate change in the world (Bellard *et al.*, 2014). Studies about the relationship between LULC changes and LST in Atlantic Forest cities are essential to support local, regional, and global plans to mitigate climate change impacts (PBMC, 2016; Willis and Petrokofsky, 2017). Nonetheless, despite its large tropical geographical extension and numerous populations potentially affected by the LST warming phenomenon, there are few studies about LULC changes and LST in Atlantic Forest Biome, with few exceptions. In this Biome, studies have focused on coastal regions, where the heat extremes phenomenon is significantly aggravated by

high air humidity (Dos Santos *et al.*, 2017; Peres *et al.*, 2018; Geirinhas *et al.*, 2021, 2019, 2017; Miranda *et al.*, 2022).

Other regions far from the coast also received attention, such as the metropolitan region of São Paulo, which encompasses 39 municipalities, where they used Aqua MODIS LST with 1 km² spatial resolution to examine the relationship between daytime and nighttime LST and each urban morphology type (Ferreira and Duarte, 2019). On the other hand, the Landsat series, which includes thermal imagery from Landsat 5 TM and 8 TIRS data, with low temporal resolution but high spatial resolution, was explored to evaluate LST patterns driven by LULC changes in Atlantic Forest Biome cities far from the coast (Carrasco *et al.*, 2020; Sayão *et al.*, 2020). The Landsat series is appropriate for local and small-scale studies (Ermidia *et al.*, 2020), and local empirical evidence regarding LULC changes and LST data from the Landsat series can provide spatially explicit information for landscape management and urban planning in cities with high urbanization in the Atlantic Forest Biome (Lemoine-Rodríguez *et al.*, 2022).

In this context, we assessed the seasonal variation of LST in response to the LULC changes over a large city in southwest Brazil during the last 36 years (1985-2020). This research aimed three specific objectives: (1) To quantify the spatio-temporal changes in LULC in Sorocaba municipality in the last 36 years (1985 - 2020) in five-year intervals; (2) To estimate from 1985 to 2020 (at five-year time intervals), for both summer and winter, the LST spatio-temporal variability over different LULC types; (3) To relate LST changes to the LULC pattern over the Sorocaba municipality due to LULC dynamics over the last 36 years.

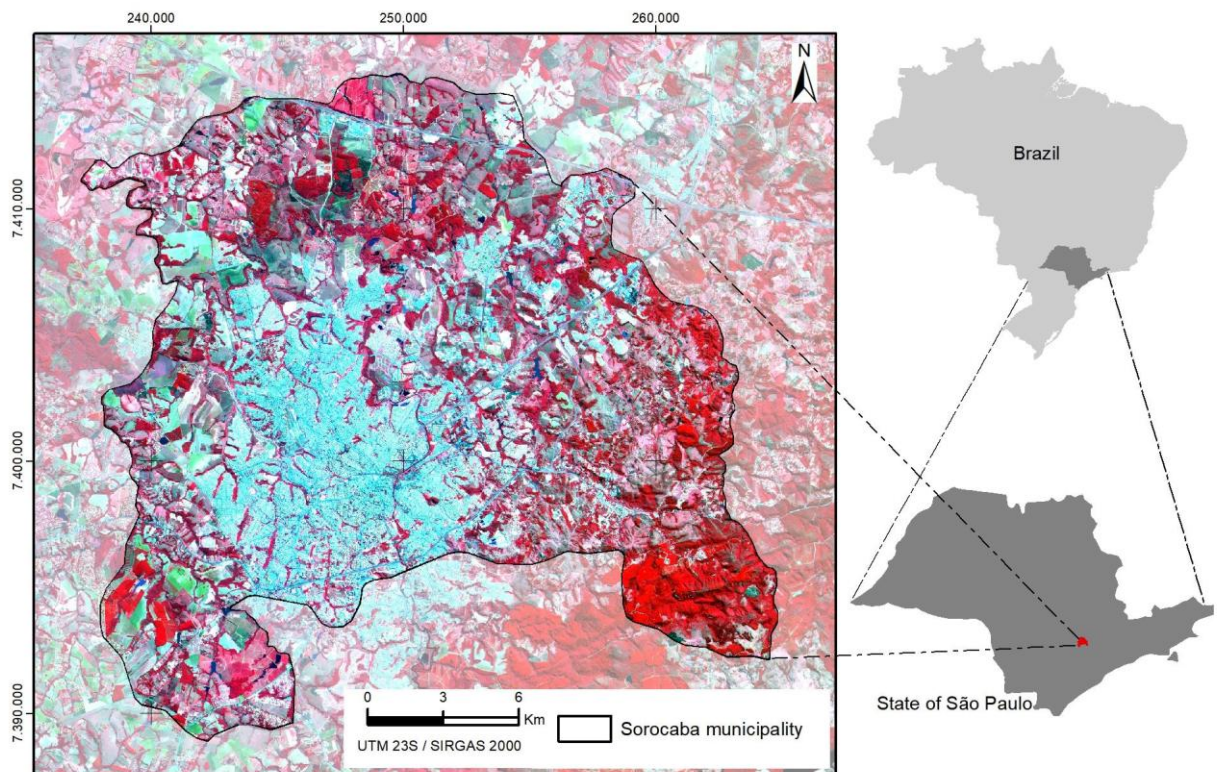
This study can provide evidence-based support to establish LULC governance at the city scale. It can help decision-makers and stakeholders formulate new policies or modify existing ones to minimize urban thermal discomfort and improve the population's wellbeing (Wang *et al.*, 2019; de Oliveira *et al.*, 2022). Additionally, it can help cities achieve Sustainable Development Goals (SDG), precisely Goal 11, to ensure inclusion, safety, resilience, and sustainability for city residents (UN, 2015). With a climate cataclysm looming and increasingly frequent and intense extreme weather events, municipal governments - responsible for urban and territorial planning through LULC management - have been encouraged by United National campaigns to promote city changes to mitigate climate change actively (UN, 2023, 2020).

3.2 MATERIAL AND METHODS

3.2.1 Study area

Sorocaba municipality has a typical urban landscape in the Atlantic Forest context in southwest Brazil (Figure 3.1). The city has approximately 45,000 ha area and a vast urban area surrounded by a highly fragmented forest composed of small forest fragments (Mello *et al.*, 2016; Ribeiro *et al.*, 2020, 2022). The local population increased from 269,830 in 1980 to 738,128 habitants in 2022. In 2014, the municipality became the headquarters of the Metropolitan Region of Sorocaba (a cluster of 27 conurbation cities); it has the ninth largest population in São Paulo state, and its population is highly urbanized - 99% living in urban areas (IBGE, 2021).

Figure 3.1 Sorocaba, State of São Paulo, Brazil. False-color composition R(NIR), G(Red), and B(Green) from CBERS-4A satellite image from 2021.

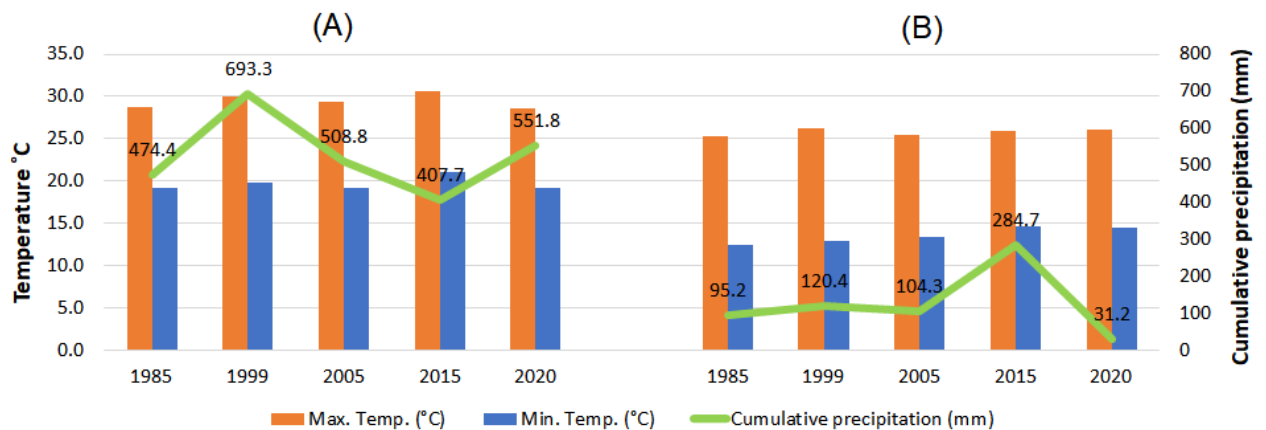


Source: prepared by the author.

The climate is classified as Cwa by the Köppen system, i.e., subtropical, with dry winter from June to September and rainy summer from December to March. The time of the year with the most cloud-covered sky starts in October and ends in March. The mean annual temperature is 22°C, with January and February being the warmest months of the year, and the mean annual precipitation is 1389 mm (CEPAGRI, 2020). Climate data from the conventional meteorological station from the National Institute of Meteorology (INMET) were obtained as

daily and monthly values of precipitation and temperature (maxima and minimum). From these climate data, averages were calculated for both summer (December to March) and winter (June to September) seasons in the selected years (1985, 1999, 2005, 2015, and 2020) (Figure 3.2). Some of the oldest climate data, such as 1990 and 2000, were not available.

Figure 3.2 Cumulative precipitation and air temperature (maxima and minimum) from the National Institute of Meteorology (INMET) in the summer (A) and winter (B) seasons in the municipality of Sorocaba, São Paulo State, Brazil.



Source: prepared by the author.

3.2.2 Land-use/land-cover (LULC) changes

Sorocaba landscape was assessed from the MapBiomias project (Souza *et al.*, 2020), available to be accessed as an asset directly from Google Earth Engine (GEE), for the years 1985, 1990, 1995, 2000, 2005, 2010, 2015, and 2020 in raster format (30-m resolution, Collection 6.0, released in August 2021). The MapBiomias classification is based on annual LULC maps (currently with 37 years of mapping covering the entire length of Brazil) based on the Landsat series with general accuracy above 85% for the Atlantic Forest Biome (Souza *et al.*, 2020).

The percentage of eight LULC types was assessed from 1985 to 2020: agriculture, forest formation, forest plantation, mosaic of agriculture and pasture, pasture, river and lake, urban area, and wetland. For the Sorocaba landscape, forest formation represents mainly native vegetation (Seasonally Dry Tropical Forest), and forest plantation mostly represents silviculture (*Eucalyptus sp.* or *Pinus sp.*).

Maps of historic LULC were first organized and new urban areas and forest formation

changes were highlighted from 1985 to 2020. Then, the raster data was transformed in shapefiles; and applied the change detection analysis (intersect tools) in ArcGIS software to assess, describe and quantify differences between LULC from 1985 to 2020 in Sorocaba through the prepared spatial data.

3.2.3 Land surface temperature (LST) data

GEE Platform was used to filter images for the selected years of 1985, 1990, 1995, 2000, 2005, 2010, 2015, and 2020 from Landsat 5 TM/TIRS and Landsat 8 OLI/TIRS, both from Collection 1 Tier 1 composites made from orthorectified scenes (30 m) using the computed surface reflectance (SR) (Table 3.1). The period corresponding to the summer (December to March) and the winter (June to September) seasons for each year were selected, and the GEE Platform returned 16 image collections containing the given images. In Sorocaba, Landsat crossing times are 12:00 PM and 1:00 PM for TM and OLI sensors, respectively.

Table 3.1. The list of products in the Google Earth Engine (GEE) catalog used for Land Surface Temperature data in Sorocaba, São Paulo State, Brazil.

Sensor / GEE Product Identifier	Year	Summer Season		Winter Season	
		Average Cloud Coverage (%)	Acquisition Date	Average Cloud Coverage (%)	Acquisition Date
Landsat-5 TM LANDSAT/LT05/ C01/T1_SR	1985	14.000	1985-01-14	2.000	1985-09-11
	1990	3.000	1990-01-28	2.000	1990-08-08
	1995-1996	5.000	1996-03-26	0.000	1995-09-07
	2000-2001	6.000	2001-01-19, 2001-03-15	0.000	2000-09-20
	2005	1.000	2005-02-22, 2005-03-10	1.000	2005-07-16, 2005-08-01, 2005-08-17
	2010	2.000	2010-02-04	0.000	2010-08-31
Landsat-8 OLI LANDSAT/LC08/ C01/T1_SR	2015-2016	3.420	2016-03-08	0.577	2015-06-26, 2015-07-28, 2015-08-13, 2015-08-29
	2019-2020	7.975	2020-02-09, 2019-12-30, 2020-01-15, 2020-02-16	0.027	2020-07-25, 2020-08-10, 2020-08-26

Source: prepared by the author.

Images with minimal cloud cover from each yearly season were selected to make a maximum value composite, and the contaminated pixels were removed from all images using the cloud mask algorithm available on the GEE platform, which equates the cloud pixel value to zero '0' (Foga *et al.*, 2017). Cloud obstructions frequently occur in tropical summer, resulting in inevitably cloud-contaminated images. The orbital frequency of Landsat series data is roughly 16 days, implying that only two images can be gathered per month; thus, finding an image without clouds is very difficult in tropical summer locations.

The LST is calculated from band 6 of Landsat-5 and band 10 of Landsat-8 images. The first process of LST retrieval is to convert the digital number (DN) of ground objects to spectral radiance using Eq. (3.1) in the TIRS sensor.

$$L_{\lambda} = M_L * DN + A_L \quad (\text{Eq. 3.1})$$

where L_{λ} is the spectral radiance ($\text{Wm}^{-2}\text{sr}^{-1}\mu\text{m}^{-1}$), M_L is the radiance multiplicative scaling factor for the band (REFLECTANCEW_MULT_BAND_n - from the metadata), A_L is the band-specific additive rescaling factor from the metadata (REFLECTANCE_ADD_BAND_N - from the metadata), DN is the calibrated standard product pixel value.

After calculating spectral radiance (L_{λ}), the brightness temperature was extracted from the radiance using Eq. (3.2).

$$TB = \frac{K2}{\ln\left(\frac{K1}{L_{\lambda}} + 1\right)} \quad (\text{Eq. 3.2})$$

where TB is the effective satellite brightness temperature in degree Kelvin, L_{λ} is the spectral radiance, and K1 ($\text{Wm}^{-2}\text{sr}^{-1}\mu\text{m}^{-1}$) and K2 ($\text{Wm}^{-2}\text{sr}^{-1}\mu\text{m}^{-1}$) are constants (K1_CONSTANT_BAND_x and K2_CONSTANT_BAND_x, where x is the number of the thermal band).

Calculating land surface emissivity (ϵ) is essential for converting TB into LST. The methodology proposed by Sobrino and Raissouni (2000), which includes the Normalized Difference Vegetation Index (NDVI) (Eq. 3.3) and Fraction of Vegetation (FV) (Eq. 3.4) algorithms, were used to calculate emissivity (ϵ) (Eq. 3.5).

Table 3.2 List of input variables considered in the Land Surface Temperature (LST) procedures in Sorocaba, State of São Paulo, Brazil.

Eq.	Input variables	Equation	Reference
(3.3)	Normalized Difference Vegetation Index (NDVI)	$NDVI = (NIR-Red) / (NIR+Red)$	(Rouse et al., 1974)
(3.4)	Fraction of vegetation (FV)	$FV = (NDVI - NDVImin) / (NDVImax - NDVImin)$	(Jing et al., 2011)
(3.5)	Emissivity (ϵ)	$\epsilon = 0.004 * FV + 0.986$	(Sobrino et al., 2004)

Source: prepared by the author.

Note: Red is the spectral radiance acquired in the red band and NIR is the spectral radiance acquired in the near-infrared regions (Rouse *et al.*, 1974). The NDVImin value accounts for 1% of the histogram pixels, and then NDVImax has a value for 99% of the pixels.

Finally, LST in degrees Celsius is calculated using Eq. (3.6).

$$LST = \frac{TB}{1 + \left(\frac{\lambda * TB}{\rho}\right) * \ln(\epsilon)} - 273.15 \quad (\text{Eq. 3.6})$$

where TB is the effective satellite brightness temperature in degree Kelvin (B6 for Landsat-5 and B10 for Landsat-8), λ is the wavelength of emitted radiance, ρ is a constant which equals to 1.438×10^{-2} mK (Artis and Carnahan, 1982) and ϵ is the emissivity. The temperature obtained in Kelvin was converted to Celsius scale by subtracting 273.15.

After correcting the temperature in Celsius, obtaining the LSTmax and LSTmin of the LST images is possible.

3.2.4 Spatial LST analysis over different LULC types

The spatio-temporal variability of LST is evaluated for the 36 years period from 1985 to 2020 (at five-year intervals), for both summer (December to March) and winter (June to September) seasons, over different LULC types through 800 random points (100 points for each LULC type) set in a geographic information system software (ArcGIS). The statistical tool used in the ArcGIS was Zonal Statistics, in which a statistic for each zone is defined based on values from another dataset. The mean of the extracted temperatures was then assessed for their trend over different LULC types for both seasons (summer and winter) from 1985 to 2020 (at five-year time intervals). The Shapiro-Wilk normality test suggested a violation of the assumption of data normality ($p < 0.001$). Thus, a non-parametric test (Dwass-Steel-Critchlow-Fligner) was

used to make pairwise comparisons and to assess LST trends over different LULC types (Vani and Prasad, 2019). The jamovi project (2021) was used for this purpose.

3.2.5 The relationship between LST the LULC pattern

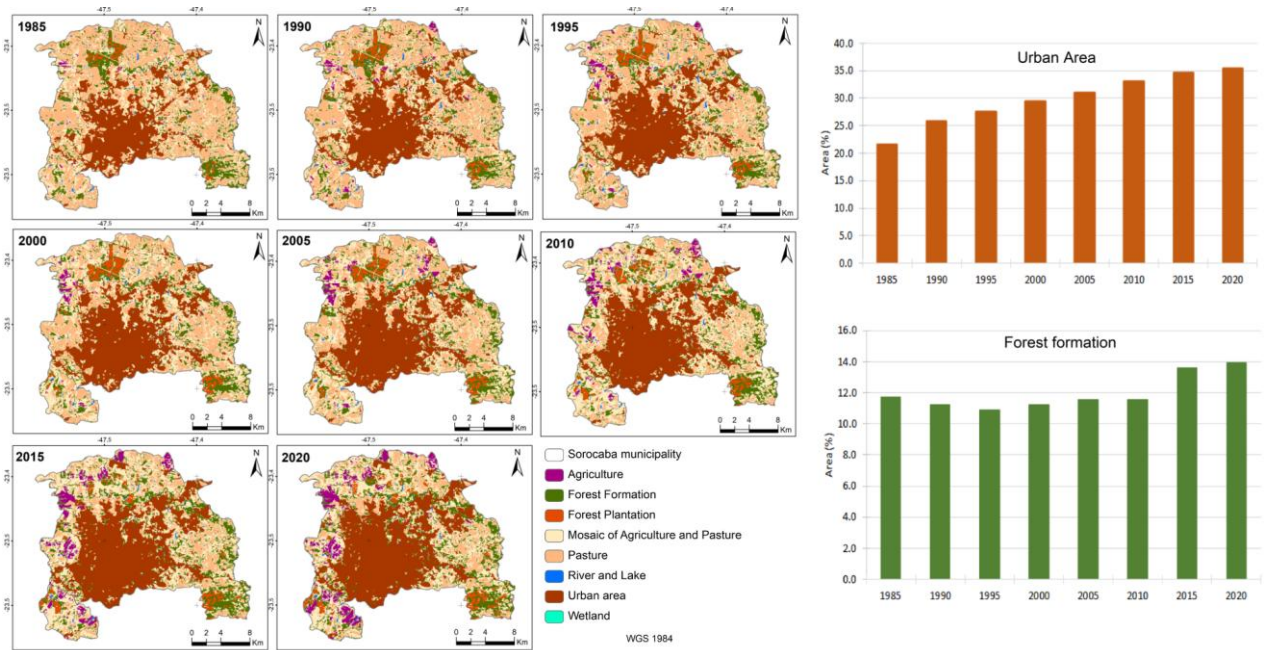
The average LST in a given area was related to the corresponding LULC patterns in the same area from 1985 to 2020 (at five-year intervals) for both summer and winter seasons based on polygon grids. These polygon grids were used to divide the study area into 2×2 km grid cells (Wang *et al.*, 2018; Yang *et al.*, 2021). The mean LST and the percentages of the eight LULC types derived from Landsat images at five-year intervals (1985 - 2020) were calculated for each grid cell using ArcGIS software. The Shapiro-Wilk normality test suggested a violation of the assumption of data normality ($p < 0.001$). Thus, a non-parametric statistical Spearman's rho test and scatter plots were used to assess the relationship between LST and the LULC patterns (Yue *et al.*, 2002). A significance equal to or less than $p > 0.05$ was established for the correlation between the studied variables. Only cells with $> 1\%$ of a LULC type were included; thus, wetlands could not be analyzed because they represent a tiny part of the landscape. All the statistical analyses and scatter plots were conducted in (The jamovi project, 2021).

3.3 RESULTS

3.3.1 Land-use/land-cover (LULC) changes

The spatial-temporal changes in LULC in Sorocaba municipality showed that the pasture, mosaic of agriculture, pasture, and urban areas were the primary land use types since 1985 (Figure 3.3). From 2015, the urban area increased and has become the main land use, achieving 35.4% of the landscape in 2020, with an area gain of 64.75% since 1985. Overall, the urban area in Sorocaba has increased by approximately 1.8% per month during these 36 years' analysis. Forest formation decreased between 1985 and 1995; since 2000, it recovered, achieving 13.9% in 2020 (Figure 3.3).

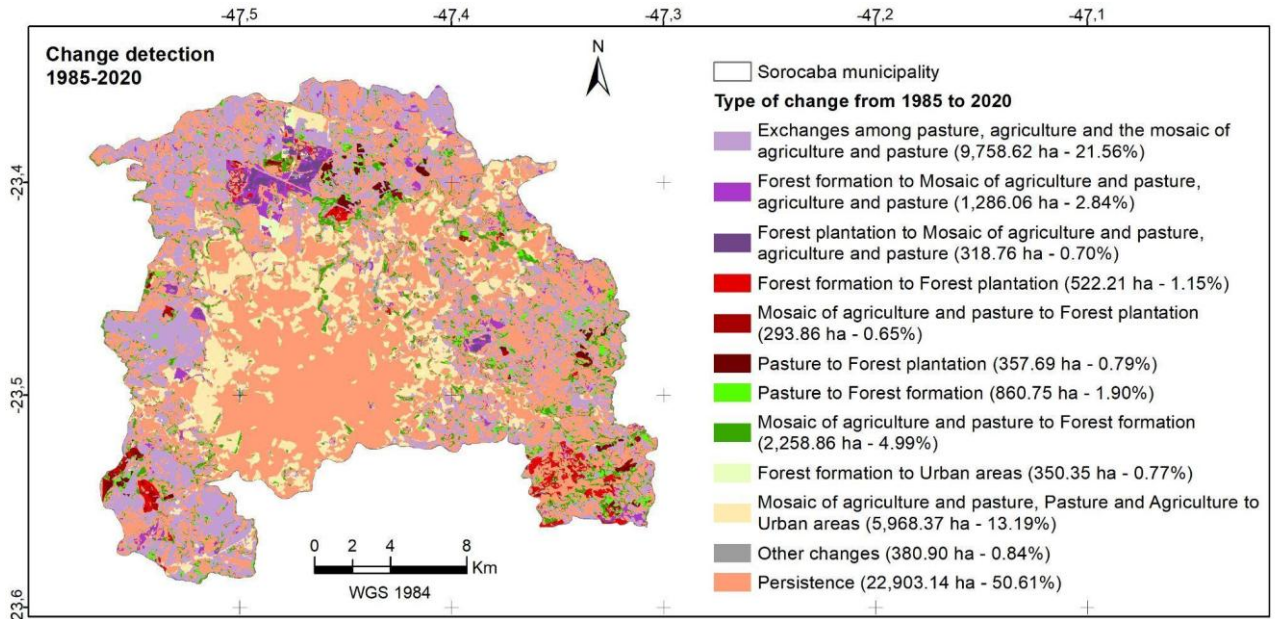
Figure 3.3 Spatial land-use/land-cover changes from 1985 to 2020 in Sorocaba, highlighting the expansion of urban areas and forest formation, State of São Paulo, Brazil. It was adapted from MapBiomias.



Source: prepared by the author.

Persistent areas (without LULC changes) in Sorocaba accounted for 50.61% (Figure 3.4), being the urban area type the more extensive persistent area (9,610 ha - 21.3%). The other half of the landscape (49.39%) had expressive LULC changes in these 36 years. Exchanges among pasture, agriculture and the mosaic of agriculture and pasture represented 21.56%, and 13.19% of them were converted in urban areas, i.e., almost 6,000 ha. Forest formation conceded almost 1,300 ha to pasture, agriculture and mosaic of agriculture and pasture, and more than 350 ha to urban areas; nonetheless, since 2000, forest formation has gained a part of the pasture class and a mosaic of agriculture and pasture (3,119.61 ha), which can contribute to the increase in forest formation total coverage.

Figure 3.4 Change detection map between 1985 and 2020, in Sorocaba, State of São Paulo, Brazil.



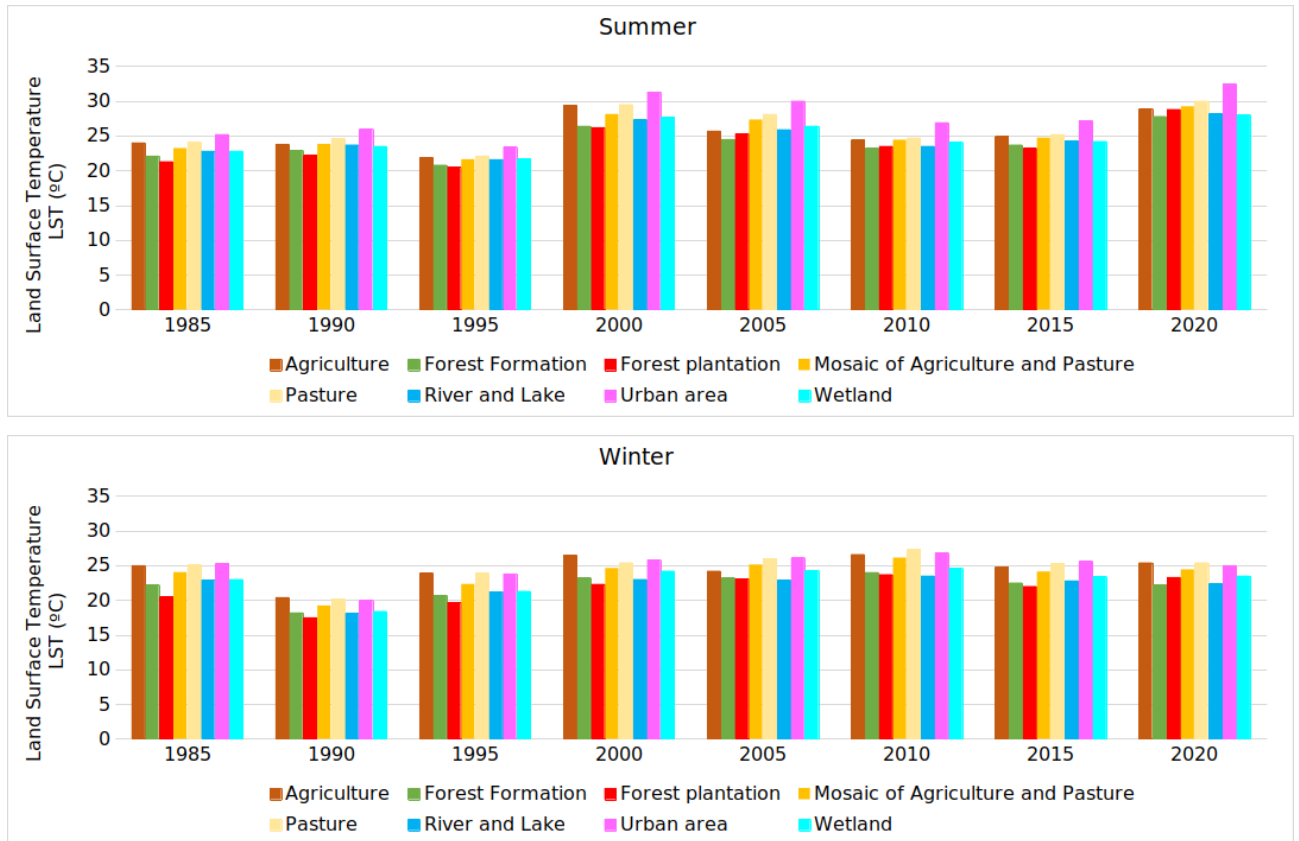
Source: prepared by the author; adapted from MapBiomias.

3.3.2 Spatial LST analysis over different LULC types

The spatial LST analysis over different LULC types showed that the mean LST significantly increased from 1985 to 2020 in both seasons (summer and winter) and for all Sorocaba LULC types. For the summer season, the mean LST for urban areas increased from 25.2°C (1985) to 32.5°C (2020), while for forest formation, the mean LST increased +5.7°C from 22.1°C (1985) to 27.8°C (2020) (Figure 3.5).

During summer, forest formation and forest plantation registered the lowest mean LST (nearly 24°C), while the urban areas achieved the highest mean LST (27.8°C), within a difference of +3.8°C, confirmed by the non-parametric Dwass-Steel-Critchlow-Fligner test ($p < 0.001$). Except in 2020, the summer LST data for the forest formation and forest plantation were statistically similar with rivers, lakes, and wetlands classes, with nearly 28°C. This year, the meteorological services of Brazil reported record-high maximum temperatures (WMO, 2021).

Figure 3.5 Mean land surface temperature (LST) for each land-use/land-cover (LULC) in summer and winter seasons from 1985 to 2020 in Sorocaba, State of São Paulo, Brazil.



Source: prepared by the author.

In this same context, the non-parametric Dwass-Steel-Critchlow-Fligner test ($p < 0.001$) confirmed that in winter, the forest formation, forest plantation, and rivers and lakes registered the lowest LST (nearly 22°C). On the other hand, pasture, agriculture, and urban areas reached slightly similar mean temperatures (nearly 24.8°C).

3.3.3 The relationship between LST the LULC pattern

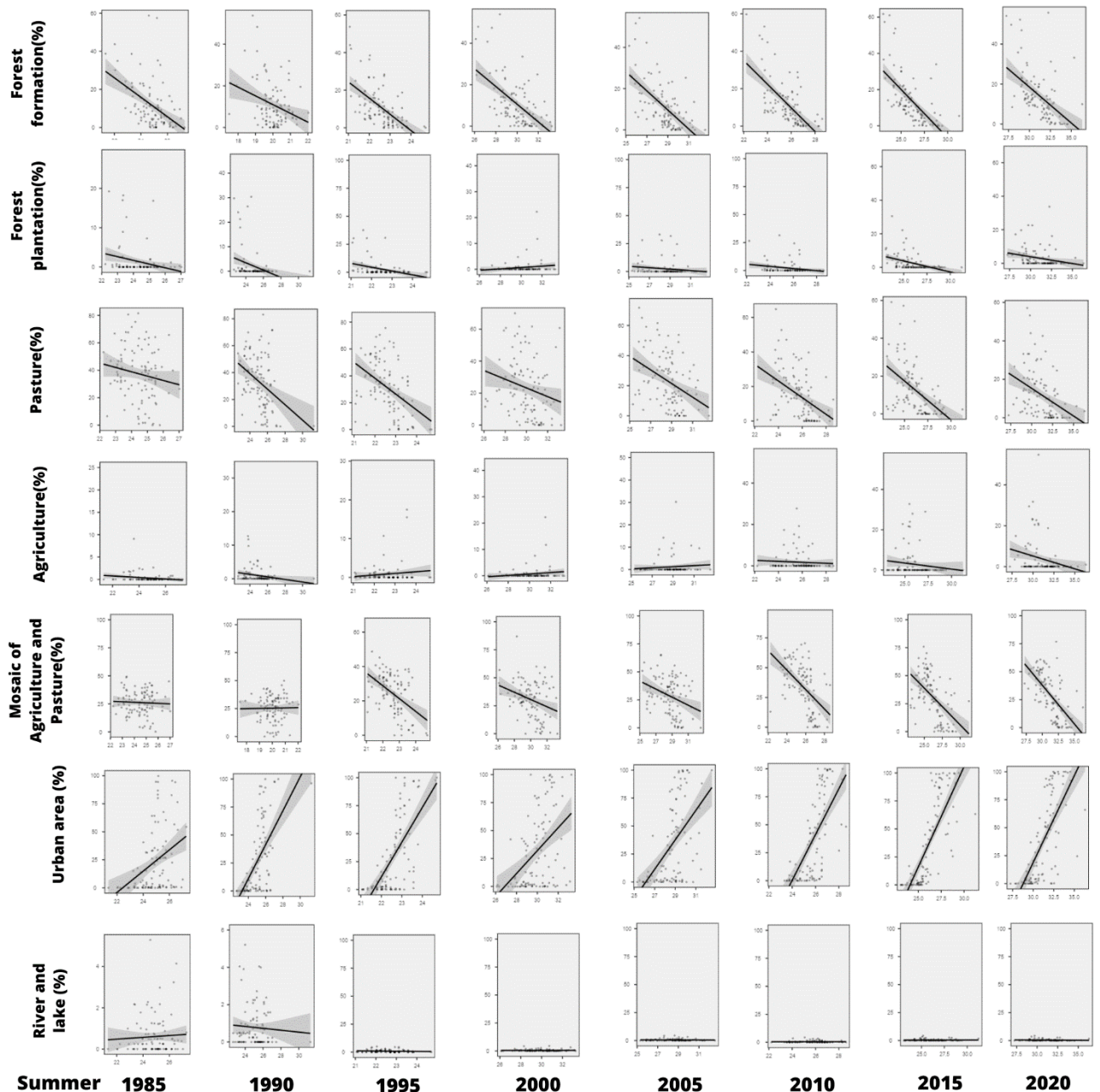
During the summer season, for all years from 1985 to 2020, most LULC types, except for agriculture, river and lake type, have presented statistically significant ($p < 0.001$) correlation with LST (Table 3.3 – Figure 3.6). The forest formation presented a moderate to strong negative correlation with LST (Spearman's rho between -0.382 and -0.75) for all years; on the other hand, urban areas presented a positive correlation with Spearman's rho between -0.433 (moderate) to -0.862 (strong) (Table 3.3 – Figure 3.6) as indicated in (Callegari-Jacques, 2009). Pasture and mosaic of agriculture and pasture were significantly negatively correlated with LST in the summer (1990-2020, except 1985). The forest plantation negatively correlated with LST during the summer.

Table 3.3 Correlation Matrix analysis between land-use/land-cover and land surface temperature (LST) during the summer from 1985 to 2020 in Sorocaba, State of São Paulo, Brazil.

Correlation Matrix	Summer	LST 1985	LST 1990	LST 1995	LST 2000	LST 2005	LST 2010	LST 2015	LST 2020
Forest Formation(%)	Spearman ρ	-0.382	-0.528	-0.647	-0.549	-0.582	-0.707	-0.75	-0.607
	p-value	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
Forest Plantation(%)	Spearman ρ	-0.236	-0.346	-0.395	-0.235	-0.327	-0.333	-0.604	-0.424
	p-value	0.017	<.001	<.001	0.017	<.001	<.001	<.001	0.001
Pasture(%)	Spearman ρ	-0.191	-0.378	-0.475	-0.319	-0.418	-0.534	-0.584	-0.500
	p-value	0.055	<.001	<.001	0.001	<.001	<.001	<.001	<.001
Agriculture(%)	Spearman ρ	0.140	-0.225	0.190	0.046	0.074	-0.125	-0.262	-0.301
	p-value	0.161	0.023	0.057	0.649	0.461	0.211	0.008	0.002
Mosaic of Agriculture and Pasture(%)	Spearman ρ	-0.016	-0.333	-0.430	-0.249	-0.311	-0.604	-0.594	-0.673
	p-value	0.873	<.001	<.001	0.012	0.001	<.001	<.001	<.001
Urban area(%)	Spearman ρ	0.433	0.631	0.692	0.465	0.589	0.802	0.862	0.767
	p-value	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
River and Lake(%)	Spearman ρ	0.104	-0.036	-0.151	-0.051	-0.067	-0.044	-0.030	-0.094
	p-value	0.297	0.724	0.131	0.610	0.506	0.657	0.765	0.346

Source: prepared by the author.

Figure 3.6 Relationship between percent of land-use/land-cover (LULC) and mean land surface temperature (LST) in summer from 1985 to 2020 in Sorocaba, State of São Paulo, Brazil.



Source: prepared by the author.

During the winter, Spearman's rho showed lower values than in the summer. Still, the forest formation continuously showed a moderate negative correlation with LST (-0,119 to -0,504, except in 2010) (Table 3.4 - Figure 3.7). In the same way, forest plantation negatively correlated with LST during the winter, except in 2005 and 2010.

Pasture, agriculture, and mosaic of agriculture and pasture did not present a correlation. The urban area showed moderate positive correlations in some years (1985-1995-2000-2015). River and lake didn't have a relationship with LST in this spatial scale (30 m), both summer and winter.

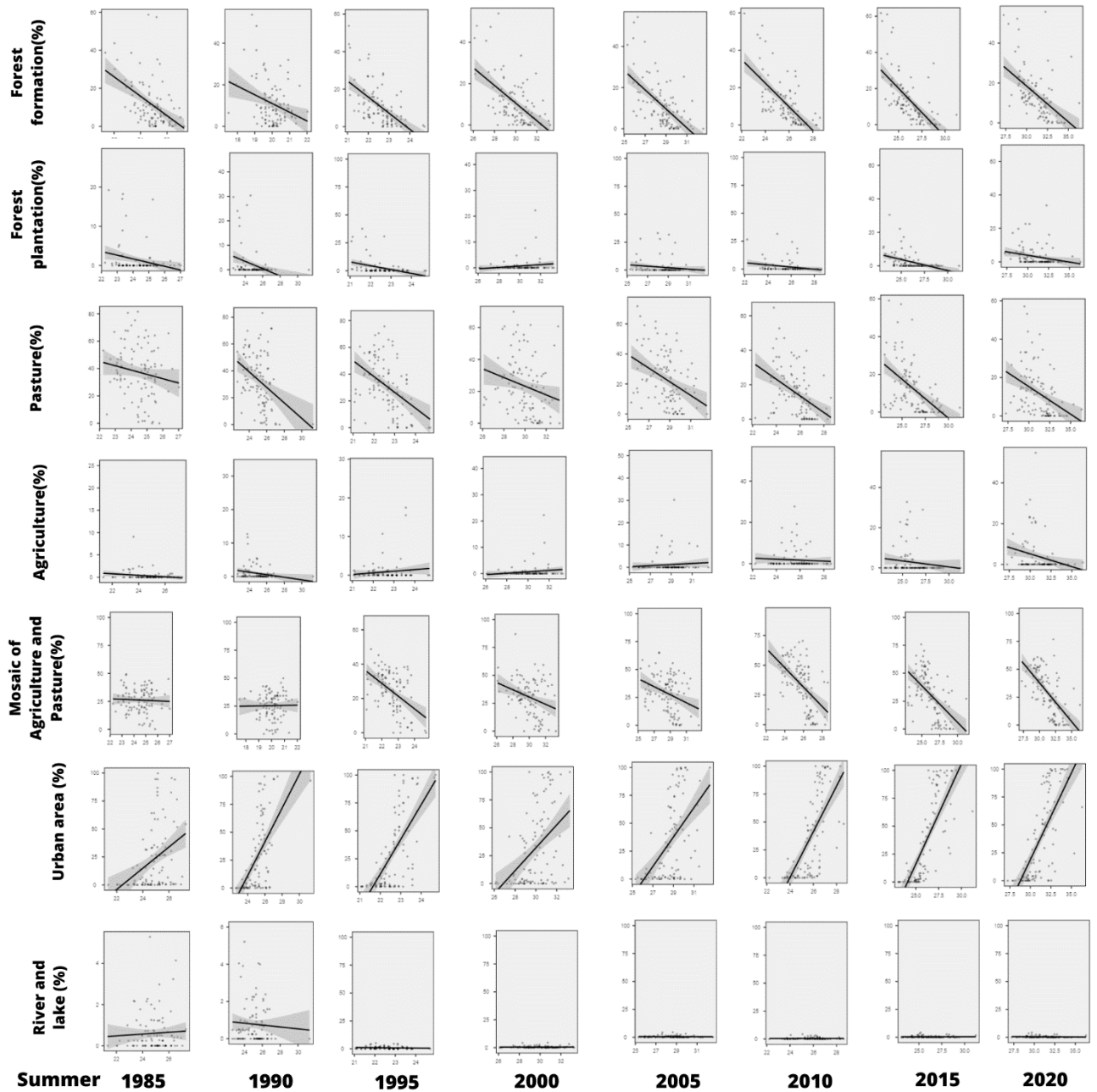
Table 3.4. Correlation Matrix analysis between land-use/land-cover (LULC) types and land surface temperature (LST) in the winter from 1985 to 2020 in Sorocaba, State of São Paulo, Brazil.

Correlation Matrix	Summer	LST 1985	LST 1990	LST 1995	LST 2000	LST 2005	LST 2010	LST 2015	LST 2020
Forest Formation(%)	Spearman ρ	-0.504	-0.22	-0.321	-0.402	-0.195	-0.119	-0.449	-0.350
	p-value	< .001	0.027	0.001	< .001	0.050	0.232	< .001	< .001
Forest Plantation(%)	Spearman ρ	-0.391	-0.202	-0.319	-0.336	-0.124	-0.141	-0.317	-0.159
	p-value	< .001	0.043	0.001	< .001	0.216	0.157	< .001	0.113
Pasture(%)	Spearman ρ	-0.091	0.128	0.062	-0.05	-0.015	0.006	-0.241	0.017
	p-value	0.363	0.203	0.537	0.617	0.879	0.953	0.015	0.863
Agriculture(%)	Spearman ρ	-0.144	0.114	-0.167	0.054	0.134	-0.075	0.077	0.046
	p-value	0.151	0.255	0.093	0.592	0.179	0.453	0.444	0.646
Mosaic of Agriculture and Pasture(%)	Spearman ρ	-0.253	0.024	-0.042	-0.055	0.047	0.165	-0.181	-0.078
	p-value	0.011	0.813	0.678	0.581	0.642	0.097	0.069	0.441
Urban area(%)	Spearman ρ	0.441	0.079	0.246	0.229	0.129	0.045	0.405	0.163
	p-value	< .001	0.433	0.013	0.021	0.197	0.651	< .001	0.104
River and Lake(%)	Spearman ρ	0.000	-0.109	-0.213	-0.166	-0.112	-0.151	0.112	0.017
	p-value	0.999	0.278	0.031	0.096	0.261	0.130	0.262	0.866

Source: prepared by the author.

Figure 3.7 Relationship between percent of land-use/land-cover (LULC) and mean land surface temperature (LST) in winter from 1985 to 2020 in Sorocaba, State of São Paulo,

Brazil.



Source: prepared by the author.

3.4 DISCUSSION

This study in the Sorocaba municipality from Southeast Brazil presented that its territory had a significant increase in urban (built-up) areas jointly with a warming of the LST over the past 36 years. The seasonal variation of LST in response to the LULC changes in this

large city within the Atlantic Forest biome shows that forest formation is substantially related to lower temperatures, and urban areas are related to the highest temperatures. These relationships were more robust in the summer, showing the importance of green infrastructure in urban areas, especially during hot seasons.

3.4.1 Land-use/land-cover (LULC) change

The results showed that Sorocaba municipality became a majority urban landscape in 2015, with more than 30% of urban areas (Figure 3.3), like other cities in the Atlantic Forest Biome (SOS Mata Atlântica, 2019). The spatio-temporal LULC dynamics in Sorocaba highlighted that pasture and mosaic of agriculture and pasture (agricultural lands) had an extensive transition to urban areas (Figure 3.4), as reported by many studies globally (Dadashpoor *et al.*, 2019; Lambin *et al.*, 2003; Pham *et al.*, 2015; Prasada and Masyhuri, 2019). Historically, urban sprawl has explored and converted agricultural land into urban areas, as seen in this case study. This process, known as peri-urbanization, involves transforming rural areas (agricultural lands) into vast urban territories (Ahani and Dadashpoor, 2021). This urban phenomenon is characterized by a mix of high-standard residential areas near green peripheries, and the informal settlements with deficient sanitation systems, and significant social and economic inequalities (UN-Habitat, 2013, 2021).

In the face of the urban sprawl, agricultural land protection in periurban areas can also contribute to limiting LULC conversion and help ensure continued proximity of food production to city consumers (IPCC, 2019; Magoni and Colucci, 2017; UN-Habitat, 2021). Thus, we emphasize the importance of the municipal government in implementing policies to protect peri-urban agriculture as a regional ecosystem service (Mulya *et al.*, 2023), with protection strategies integrated with food-system planning strategies, even if it results in a reduction of the city tax collection from built-up areas. We also support and recommend implementing urban agriculture in public spaces and vacant land (McClintock *et al.*, 2013; Newell *et al.*, 2022). Urban populations continue to grow, and these activities can play an essential role in food production, benefiting people, including vulnerable residents, and operating in synergy with urban ecosystem conservation (UN-Habitat, 2021).

Although the urban areas had a massive sprawl in Sorocaba, the native vegetation (forest formation) had a small area increase from 1985-2020 (Figure 3.3 and Figure 3.4). Native vegetation (Atlantic Rainforest) has been under legal protection since 1993 through Federal decree nº 750/936 (Brasil, 1993), which established conservation and suppression criteria for

native vegetation, restoration of Permanent Preservation Areas (mainly riparian zones), and landscape connectivity. In these 36 years (1985-2020), a small portion of native vegetation was mostly naturally restored in Sorocaba. However, in the last few years, Brazil has experienced an environmental setback that weakened the legal coverage of the current national forest legislation, and as a result, riparian zones, previously protected in urban areas, have been reduced or even eliminated (Brasil, 2021). Currently, local municipalities have assumed more authority than the federal government, based on the assumption that they can decide on Protected Areas within their self-demarcated urban areas. Thus, there is a growing relevance of the conservation and restoration of green infrastructures in Brazilian cities by the design of municipal policies, such as the creation of Protected Areas, anthropic grassland and riparian zone restoration, besides incentives to restore landscape connectivity, among others (Ribeiro *et al.*, 2022).

Municipal policies should prioritize the implementation of mitigation strategies to compensate for the negative impact of expanding the impervious surface (Lapola *et al.*, 2019). The impervious surface is sprawling, and the cities are experiencing record-high temperatures (Geirinhas *et al.*, 2019, 2017; Vani and Prasad, 2019); in this regard, identifying the relationship between LULC patterns and LST can help to establish evidence-based governance in LULC management and environmental monitoring.

3.4.2 LST-LULC analyses

When assessing LST across different LULC types in both summer and winter seasons from 1985 to 2020, a consistent increase in LST was observed (Figure 3.5), aligning with the global trend of land warming (IPCC, 2018; WMO, 2021). The urbanization process in the municipality of Sorocaba, characterized by the transformation of landscapes and increased impervious areas, notably contributed to the rise in LST (Wang *et al.*, 2016). The impact of land conversion on LST, particularly the transformation of forest and agricultural lands into urban areas, is evident, echoing the observations in cities in India (Pandey *et al.*, 2022).

From 1985 to 2020, the mean temperature in urban (built-up) areas during the summer increased by 7°C. In 2020, the mean temperature in urban areas was 32.5°C and 27.8 °C in forested areas during the summer (Figure 3.5). This phenomenon resonates with the broader context of land surface warming in Brazilian urban regions, which has been above the global average (IPCC, 2014), emphasizing the significance of the relationship between LST and LULC

patterns (Stone *et al.*, 2010; Estoque *et al.*, 2017; Vani and Prasad, 2019; Zullo *et al.*, 2019; Adulkongkaew *et al.*, 2020; Mondal *et al.*, 2021; Pandey *et al.*, 2023).

In our study, forest formation presented a negative correlation with LST and urban areas presented a positive correlation in both seasons (Figure 3.6 and 3.7). During the summer, pasture, mosaic of agriculture and pasture, and forest plantation were negatively correlated with LST. The same was observed by Pandey *et al.* (2023) and Mondal *et al.* (2021) in cities in India, where LST was negatively correlated to spectral indices related to water (MNDWI) and vegetation cover (NDVI), and positively correlated to built-up indexes (e.g. NDBI). Despite not showing a significant correlation with LST as it represents a small portion of the landscape - our study used 30 m as the spatial scale - the water coverage presented, together with forest formation and forest plantation, the lowest LST during the winter corroborating these previous studies. Future research may benefit from exploring different scales and concerns about how water bodies are the LST-reducing surface (Guha *et al.*, 2022).

Urban sprawl leads to the increase in impervious surface, reducing the vegetation cover as forest formations and agricultural areas that help to keep lower temperatures. The urbanization process also channels waterways, which can also affect surface temperatures. This expansion of the urban area forms decentralized cities, contributing to low-density residential areas, segregation by income and social class, exploration of agricultural land, and more car-dependent systems (UN-Habitat, 2013, 2020). This trend has several impacts on health, including reduced physical activity and worsened air pollution, mainly through CO² and air pollutant emissions, i.e., greenhouse gas emissions. These emissions, together with impervious surfaces, increase the LST in cities and their surroundings, promoting the urban heat island phenomenon (Landsberg, 1970; UN-Habitat, 2013; IPCC, 2018; Ravanelli *et al.*, 2018; Ranagalage *et al.*, 2020). The municipal governments are responsible for urban and territorial planning through LULC management, a fundamental tool for mitigating urban heat islands. Thus, we recommended LULC governance for enhancing urban resilience, including a shift toward compact city planning, protected agricultural lands around cities, and increased availability of green infrastructure in urban and periurban areas (Dodman *et al.*, 2022). Initiatives like urban greening and the utilization of vacant lands for green infrastructure or urban agriculture are proposed as climate adaptation measures in consolidated urban areas (Sanchez and Mesquita Pellegrino, 2016; Guha and Govil, 2023).

Several studies emphasizing the importance of green infrastructure in reducing LST (Sun and Chen, 2017; Manickathan *et al.*, 2018; Peng *et al.*, 2018; Molina-Gómez *et al.*, 2022), including the IPCC reports, resonate with our findings. In this large city in the Atlantic Forest

Biome, areas with forest formation registered the lowest LST (Figure 3.5) acting as a heat sink. Thus, the influence of green infrastructure on LST cannot be disputed, even in tropical regions, with highly fragmented forests, extremely high temperatures, and long periods of high humidity levels, as indicated in other studies (Ferreira and Duarte, 2019; Lapola *et al.*, 2019; Manoli *et al.*, 2019). These areas bring essential benefits to the cities, primarily through direct shading and evapotranspiration, which can lower temperatures and create a cool island inside an urban area (Oke, 1989; Childers *et al.*, 2019). As seen in Imphal City, India, proper land conversion strategies, particularly preserving forest and agricultural lands, can mitigate LST rise (Pandey *et al.*, 2022). An integrated approach to adaptation, blending green infrastructure with traditional engineered infrastructure, is suggested for effective LULC governance to enhance urban resilience, i.e., they must be embedded into the architectural designs and infrastructures across neighborhood and city scales within their particularities (Dodman *et al.*, 2022).

The seasonality of LST by LULC was explored in this study, revealing variations between seasons. Urban areas exhibited similar LST to other LULCs during the winter, such as pasture, agriculture, or a mosaic of agriculture and pasture, while in summer, the urban area had the highest LST compared to other LULC types. Besides, rivers and lakes achieved a similar LST in winter with forest formation and forest plantation. The amount of solar thermal radiation received in the winter is smaller than in the summer; thus, the temperature difference between LULC types decreases, indicating unreliable statistics (Wu *et al.*, 2021; Yang *et al.*, 2021). In this regard, we consider summer the most suitable season for studies that survey LST warming in Atlantic Forest Biome cities. Future research may benefit from exploring different time-frames, image compositing methods, and cloud-covering removal techniques when estimating LST for tropical cities. Furthermore, LST can be estimated by comparing the results with those derived from other algorithms or satellite sensors (Guha and Govil, 2021).

Considering the climate emergency highlighted by the IPCC and United Nations Climate Change Conference (COP27), land-use policies, particularly urban and territorial planning, must prioritize LULC governance for urban resilience. As observed in Imphal City, India, proper land conversion strategies, particularly preserving forest and agricultural lands, can mitigate LST rise (Pandey *et al.*, 2022). Urban populations will increase in the following years, and actions such as protecting agricultural land from urban sprawl, urban sprawl management, and increasing urban green infrastructure must be used to promote climate and environmental justice, human health, and global ecosystem health. These are just some necessary actions to respond to the failure of the existing urban development models, mainly in

Latin American cities, such as Brazil, where cities have grown without urban and territorial planning and notably with extreme territorial inequality (Keith *et al.*, 2022).

3.5 CONCLUSION

Encompassing a comprehensive analysis of spatio-temporal changes in LULC and LST over the past 36 years (1985-2020) in Sorocaba municipality, our study has provided evidence-based knowledge into the complex interplay between urban development, landscape dynamics, and temperature variations in this large city within the Atlantic Forest Biome.

The spatio-temporal analysis of LULC data and LST for both summer and winter seasons has unveiled the substantial urban sprawl experienced by Sorocaba, with an area gain of 64.75% since 1985. Between 1985 and 2020, urban areas experienced a significant increase in land surface temperature, particularly during summer, with an increase of more than 7°C, highlighting the urban heat. Conversely, forest formations demonstrated a slight area increment, primarily attributed to natural recovery, and registered the lowest LST and a high negative correlation with LST in both seasons. This dichotomy highlights forest ecosystems' vital role in mitigating urban heat, particularly during summer, when the forest formation showed a strong negative correlation with LST (Spearman's rho between -0.382 and -0.75) in all years. Besides, we believe that summer is the most suitable season to study LST warming in cities located in the Atlantic Forest Biome. This crucial research will aid in understanding the effects of rising temperatures and will equip us to devise practical solutions to mitigate its consequences.

The specific loss of pasture and agricultural mosaic classes due to urban expansion highlights the need for conservation policies to regulate and mitigate uncontrolled LULC conversions, preserve peri-urban agricultural areas, and maintain proximity to urban consumers.

Our findings emphasize the pivotal role of green infrastructure in reducing urban LST. The high negative correlation between LST and forest formation underscores the importance of preserving and expanding green areas in urban and periurban regions. To enhance urban resilience, we suggest implementing LULC governance measures, including compact city planning, safeguarding agricultural lands, and promoting urban greening initiatives. Integrating green infrastructure with traditional engineered infrastructure is crucial for achieving optimal results.

This study serves as a clarion call for a paradigm shift within municipal governance, urging a prioritization of sustainable urban development measures. The technical-scientific evidence presented here contributes significantly to discussions about the impact of LULC changes on LST in tropical cities, especially in Latin American urban settings. The recommended climate adaptation policies aim to improve urban health, addressing the growing challenges of climate change and rapid urbanization. As we find ourselves in a climate emergency, the lessons learned from Sorocaba can guide similar urban centers in Latin America and other tropical areas toward more resilient and sustainable futures.

This study has certain limitations, such as the spatial scale and variation in the LST season. Future research in cities within the Atlantic Forest biome can improve LST estimates by exploring different time-frames, seasons, image-compositing methods, spatial scales, and cloud-cover removal techniques. Additionally, LST can be estimated by comparing results obtained from other algorithms or satellite sensors.

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4 PRIORITIZATION OF NEW GREEN INFRASTRUCTURES AIMED AT PROTECTING URBAN BIODIVERSITY

Abstract

Urban expansion threatens ecosystems, biodiversity, and public health. Green infrastructure helps promote biodiversity and improve air and water quality, and public health benefits. This study aimed to develop a geospatial model to support decision-making on identifying priority areas for increasing green infrastructure to maintain biodiversity in urban landscapes, focusing on the Atlantic Forest Biome. The model was based on Multicriteria Evaluation and a mixed approach to define the criteria, integrating literature review and participatory techniques. Using the Weighted Linear Combination, the model classified areas into low, medium, and high priorities based on four criteria: landscape connectivity, proximity to Protected Areas, rivers and lakes, and distances from streets and roads. The high-priority areas were identified as the most suitable for implementing new green infrastructure. Results provide insights for urban managers seeking to expand green networks and biodiversity-driven infrastructure, transforming urban areas into resilient ecosystems addressing the challenges posed by climate change.

Keywords: Urban planning, urban green areas, ecosystem benefits, urban resilience, Multicriteria Evaluation.

4.1 INTRODUCTION

At present, cities confront the urgent challenge of conserving natural habitats to facilitate the expansion of biodiversity within urban environments. This endeavor is critical for ensuring the continuous supply of essential ecosystem services and promoting human wellbeing (Parris *et al.*, 2018). A highly effective approach is to implement nature-based solutions, especially by expanding green infrastructure in cities (UN-Habitat, 2020; Dodman *et al.*, 2022).

Providing cities with a multitude of social and ecological benefits, green infrastructure serves as a Nature-Based Solution. It plays a crucial role in helping cities adapt to climate change and achieve the Sustainable Development Goal (SDG), especially Goal 11, which focuses on ensuring inclusive, safe, resilient, and sustainable cities (Privitera and La Rosa, 2018; UN, 2020, 2015).

To design the green infrastructure expansion in cities and promote urban biodiversity increase, it is crucial to consider the interconnected aspects of both the physical and biological elements of the landscape. Additionally, collaboration and engagement with relevant stakeholders are essential to ensure the success of such initiatives (Snäll *et al.*, 2016; Tauhid and Zawani, 2018). To this end, an integrated approach combining participatory techniques, which reveal local people's opinions, and Multicriteria Evaluation methods have been used to prioritize areas for biodiversity conservation worldwide (Orsi and Geneletti, 2010; Valente *et al.*, 2017; Sumida and Valente, 2019; Strassburg *et al.*, 2020).

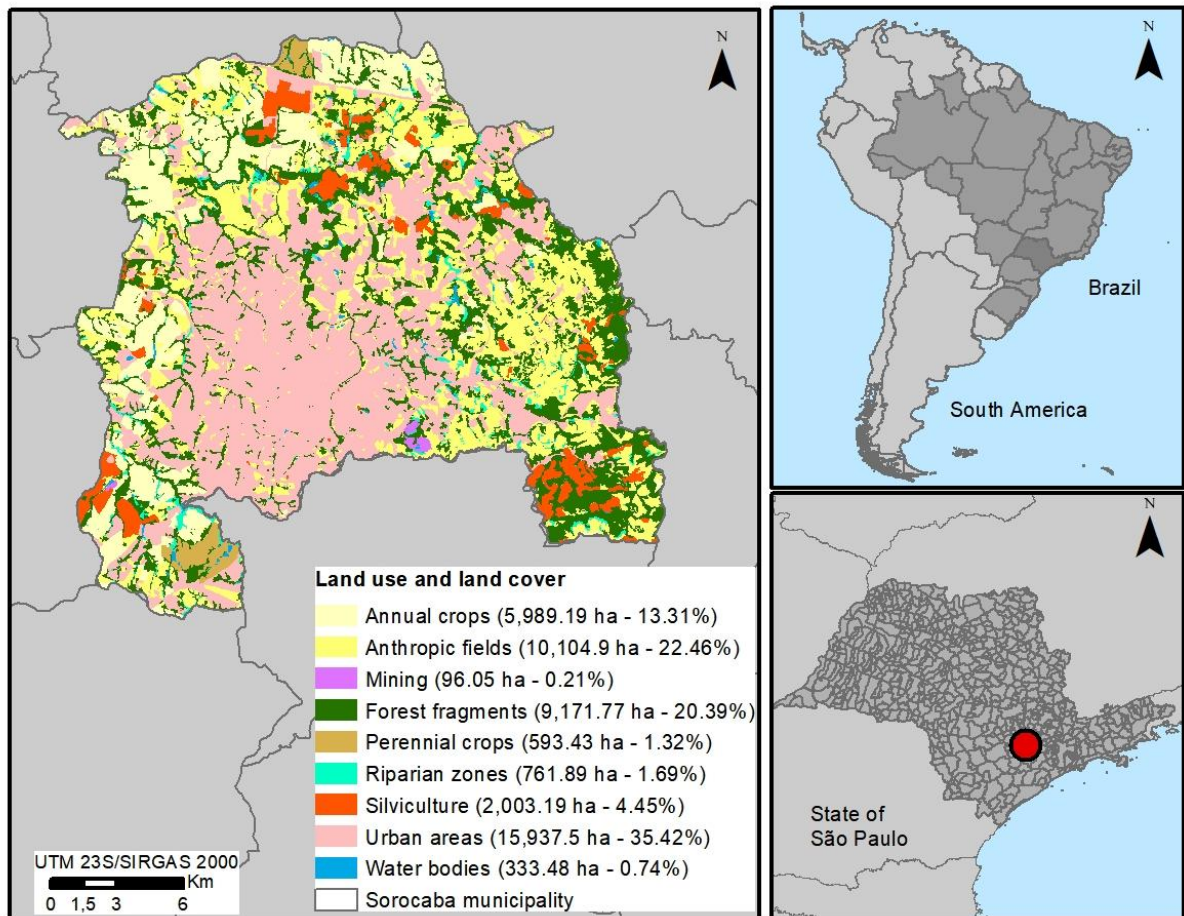
In this context, the objective of this study was to develop a geospatial model aimed at supporting decision-making in identifying priority areas for expanding green infrastructure to maintain biodiversity in urban landscapes, particularly those within the Atlantic Forest Biome. To achieve this, a model based on Multicriteria Evaluation and a mixed approach to defining the criteria, using literature review and participatory technique, was applied to a highly urbanized municipality located within the Atlantic Forest Biome, Brazil, which is recognized as a global biodiversity hotspot.

4.2 MATERIAL AND METHODS

4.2.1 Study area

The study area encompasses the municipality of Sorocaba, located in the southern region of the Brazilian Atlantic Forest (Figure 4.1). With a total area of approximately 450 km², the municipality is predominantly urbanized, with 99% of its population living in urban centers (IBGE, 2023). The region is characterized by high forest fragmentation, consisting of small and poorly connected forest fragments (Mello *et al.*, 2016; Ribeiro *et al.*, 2022).

Figure 4.1. Sorocaba municipality, state of São Paulo, Brazil: location and land use and land cover data for 2022.



Source: Adapted from Ribeiro, Mello and Valente (2020).

4.2.2 Model

The spatially explicit decision support model was developed within a Geographic Information System (GIS) environment, incorporating insights from both bibliographic review and participatory techniques, as well as the Weighted Linear Combination method, a widely used method in Multicriteria Evaluation (Voogd, 1982). The model's structure involved the pre-definition of criteria by a literature review - used to search and collect information from published sources about the relationship between green infrastructure and urban biodiversity. These findings of the literature review were used to engage with researchers, decision-makers, and civil society stakeholders for discussions on public environmental policies within existing municipal spaces. Additionally, applying a participatory technique consultation with experts played a vital role in refining the model.

4.2.3 Criteria

The first step involved compiling a set of criteria through a combination of literature review and participatory technique. The literature review prioritized academic publications in English, accessed through the Web of Knowledge database, using search terms such as: (MCE OR multicriteria) AND biodiversity AND urban. This search encompassed publications available up to September 2022.

The criteria identified from the literature review were further discussed during a workshop on participatory technique held on September 14, 2022. This event occurred at a pre-established venue during a monthly meeting of the Municipal Development Council of the Environment in Sorocaba (COMDEMA). Subsequently, additional input was gathered through expert consultation using an electronic form (approved by the Federal University of São Carlos Ethics Committee) as part of the participatory process. The criteria were evaluated in pairs by experts using an Analytical Hierarchy Process (AHP) based on a scale ranging from 0.33 to 3 points (Table 4.1).

Table 4.1: Paired comparison scale for defining factor weights according to the Analytical Hierarchical Process (AHP).

Rating	Level of importance of factors for the decision-making process
0.33	The preferred characteristics are slightly more important
0.50	The preferred characteristics are moderately more important
1	Two characteristics are equally important
2	The preferred characteristics are strongly more important
3	The preferred characteristics are absolutely more important

Source: Adapted from Saaty (2008).

The comparison values obtained from expert input support the creation of the paired comparison matrix, which was implemented in a Python script for this study. This matrix enables the calculation of factor weights (Saaty, 2008), with the consistency rate considered adequate when lower than 0.10 (Malczewski *et al.*, 2003). Factor Weights represent the relative importance, as perceived by experts through participatory technique, of each criterion under consideration (Malczewski *et al.*, 2003; Eastman, 2011).

4.2.3.1 Criteria standardization

The criteria were normalized to a standard scale, ranging from 0 - 1 (Valente *et al.*, 2021). An increasing linear fuzzy set membership function (Eq. (4.1)) was used to standardize the criteria maps to a scale of 0 - 1.

$$x_i = \left(\frac{R_i - R_{min}}{R_{max} - R_{min}} \right) m \quad (\text{Eq. 4.1})$$

where R_i is the original score, and m is the standardized scale (0-1).

4.2.3.2 Criteria aggregation

The Weighted Linear Combination method (Voogd, 1982) was used to aggregate criteria (Eq. (4.2)).

$$S = \sum w_i x_i \quad (\text{Eq. 4.2})$$

where: S is suitability; w_i is the weight of factor i ; and x_i is the criterion score of factor i (Drobne and Lisec, 2009).

The aggregation process results in a priority map from 0 to 1, where 1 represents the highest importance according to the study's objective, indicating areas with high priority. Conversely, areas with a value of zero (0) are considered of the least importance.

4.2.4 Definition of priority classes for increasing green infrastructure

The histogram of the priority maps was evaluated, and the main statistical parameters. Including mean (μ), standard deviation (σ), and variance (σ^2), were extracted. Subsequently, classes associated with low, medium, and high priority for the allocation of new green infrastructure for biodiversity in an urban landscape were delineated based on the obtained values. Specifically, the classes were defined as follows: Low priority [0 to $\mu - \sigma$]; Medium priority [$\mu - \sigma$ to $\mu + \sigma$] and High priority [$\mu + \sigma$ to 1] (Louzada *et al.*, 2009).

4.2.5 Model validation

To validate the model, priority classes (low, medium, and high) were characterized based on information on land use and coverage, as well as landscape characteristics related to their criteria through a cross-tabulation (Vettorazzi and Valente, 2016).

4.3 RESULTS

Through the combination of literature review and the participatory technique Workshop at COMDEMA in Sorocaba, criteria with spatial attributes were selected for prioritizing areas for biodiversity in urban landscapes. Four key criteria were identified: landscape connectivity, proximity to Protected Areas (PAs), proximity to rivers and lakes, and distances from streets and roads.

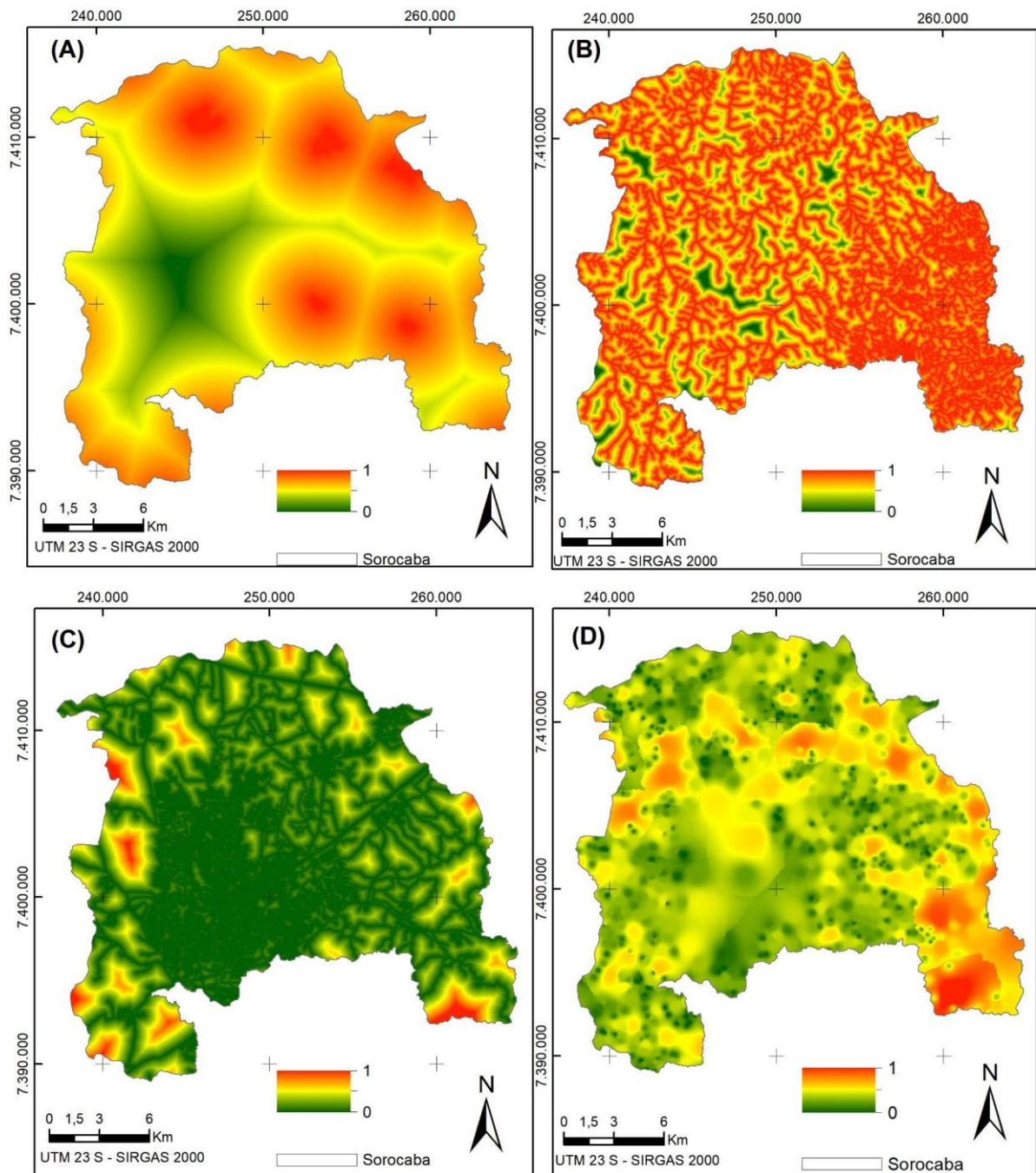
The landscape connectivity index for Sorocaba municipality was obtained from previous research (Ribeiro *et al.*, 2022), representing the degree to which the landscape allows or hinders movement between forest fragments. Additionally, vector data of PA boundaries, rivers and lakes, and streets and roads for 2018 were provided by the Department of the Environment of the Sorocaba Municipality.

Nineteen (19) expert responses were collected through the AHP process to assess the importance of the criteria. These responses helped identify planning priorities for stakeholders when defining new areas for green infrastructure to preserve biodiversity in an urban context. The Factor Weights resulting from this process were determined as follows: Landscape connectivity = 0.403; Proximity to PAs = 0.325; Proximity to rivers and lakes = 0.194, and Distance from streets and roads = 0.078. The consistency rate reached 0.063, falling within the appropriate range according to Malczewski *et al.* (2003).

4.3.1 Standardized criteria

The criteria standardization process conducted using the linear fuzzy set results in continuous values ranging from 0 to 1 (Figure 4.2). In this standardization scale, areas with the highest priority areas-those with the highest connectivity values, situated near PAs, close to rivers and lakes, and distant from streets and roads - are associated with values closer to 1 (Figure 4.2). These high values signify the highest level of suitability for biodiversity conservation and green infrastructure development within urban landscapes.

Figure 4.2 Standardized suitability for (A) proximity to Protected Areas, (B) proximity to rivers and lakes, (C) distance to streets and roads, and (D) connectivity of the landscape for the Municipality of Sorocaba, State of São Paulo, Brazil.



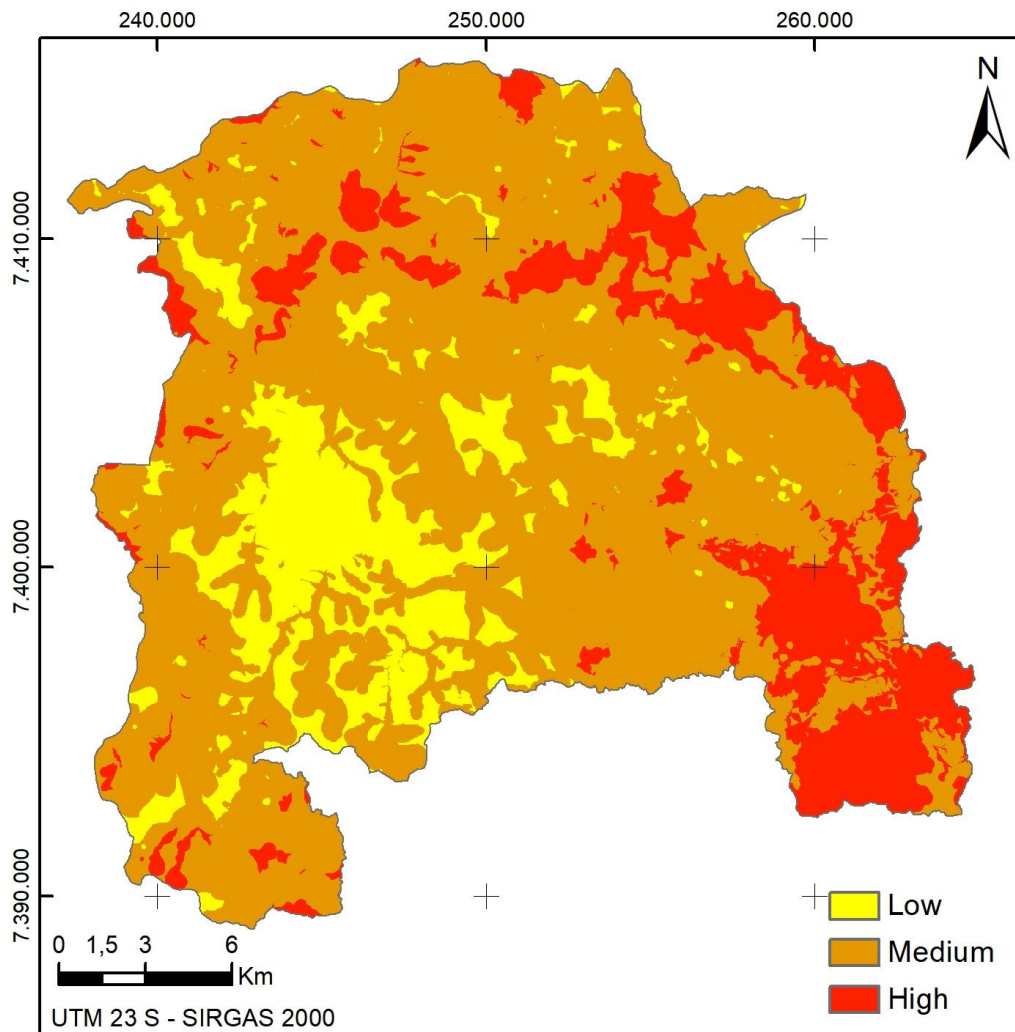
Source: prepared by the author.

4.3.2 Criteria aggregation and priority classes definition

The aggregations of different groups of Factor Weights have produced a map with continuous values ranging from 0 to 1. In this representation, a value of 1 indicates the highest priority area for enhancing green infrastructure. Based on these values, priority classes for the allocation of new green infrastructure for biodiversity have been established, distinguishing between low, medium, and high priority areas. These priority classes help guide decision-

makers in strategically allocating resources and efforts towards increasing green infrastructure in urban landscapes to promote biodiversity (Figure 4.3).

Figure 4.3 Priority areas for allocating new green infrastructure of the Municipality of Sorocaba, State of São Paulo, Brazil.



Source: prepared by the author.

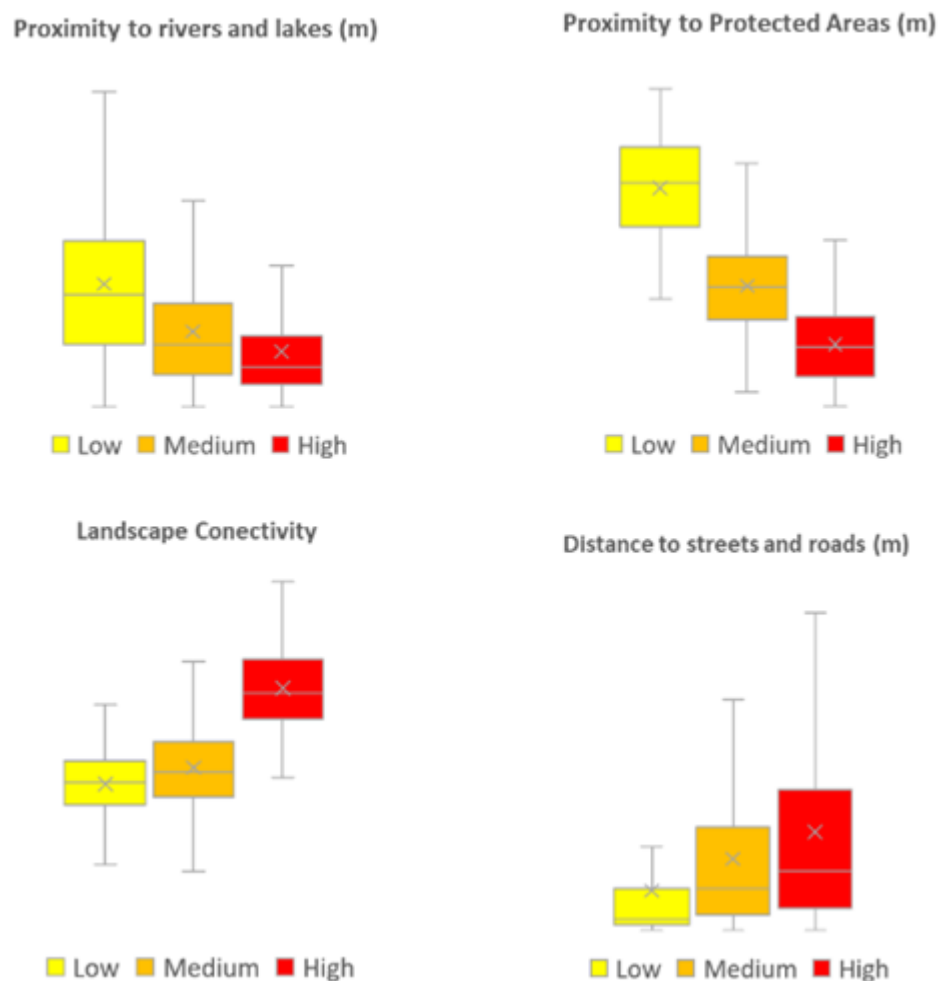
4.3.3 Model validation

High-priority areas for enhancing green infrastructure are characterized by their proximity to rivers and lakes, their close proximity to PAs with high connectivity values, and their distance from streets and roads (Figure 4.3).

Conversely, low-priority areas consist of regions situated far from rivers and lakes, distant from PAs, possessing lower connectivity values, and closer to streets and roads. The medium-priority areas fall between these extremes, with values that represent a balance

between low and high priorities. These distinctions aid in effectively identifying and prioritizing areas for the allocation of green infrastructure resources, ensuring targeted efforts towards biodiversity conservation in urban landscapes (Figure 4.4).

Figure 4.4 Landscape characteristics related to priority class (low, medium, and high) to subsidize the validation process for prioritizing areas for green infrastructure increase in Sorocaba, State of São Paulo, Brazil.



Source: prepared by the author.

4.4 DISCUSSION

The map generated through the use of Factor Weights by participatory technique underscores the pivotal role of stakeholder involvement in environmental modeling (Voinov *et al.*, 2016), especially in studies conducted at the city level. The decision to adopt the participatory technique is grounded in the recognition that as human activities increasingly

impact the environment and natural resources, socio-ecological systems become more complex and unpredictable. This complexity poses challenges in identifying optimal solutions and selecting the most suitable management practice (Voinov and Bousquet, 2010).

By engaging stakeholders, who possess diverse perspectives and local knowledge, in the modeling process, a more comprehensive understanding of the system is attained. This collaborative approach enables the exploration of a wider range of potential solutions and enhances the likelihood of identifying effective strategies for managing environmental challenges in urban settings. Stakeholders gave greater importance to areas identified as high priority for increasing green infrastructure - those with exceptional connectivity indices, proximity to PAs, close adjacency to rivers and lakes, and farthest from streets and roads. Through amalgamation of these four criteria and weighting them according to the local stakeholder priorities, the spatial model identified hotspots where green infrastructure holds the greatest potential for fostering ecological resilience and biodiversity (Figure 4.3). This approach provides valuable insights for urban landscape planning (Meerow and Newell, 2017) enabling targeted efforts to enhance biodiversity conservation and promote ecological sustainability within urban environments.

Medium-priority areas encompass the majority of the landscape, aligning with findings from previous studies (Malczewski *et al.*, 2003; Valente and Vettorazzi, 2008; Valente *et al.*, 2021) that highlight their significance in providing risk-averse solutions for decision-making processes. These areas typically strike a balance between various factors, offering a level of suitability that may not be as high as high-priority areas but is still considered acceptable and feasible for green infrastructure development. Leveraging medium-priority areas in decision-making processes can help ensure broader coverage and inclusivity in urban landscape planning initiatives, while also mitigating potential risks associated with focusing solely on high-priority regions.

The categorization of priority areas is a critical stage in the model construction process, as it entails disseminating the achieved results, which will be used by interested parties, such as those involved in urban conservation and restoration projects, urban silviculture, and other “green” interventions. In this study, a categorization method based on the mean and standard deviation of spatial data was used. However, it is essential to recognize that this categorization approach can and should be tested in different scenarios and categories in future projects. For instance, a continuous prioritization scale ranging from low (1) to high priority (10), without distinct classes, was adopted by Meerow (2020) to increase green infrastructure in New York. Exploring different categorization approaches enables flexibility and adaptability to diverse

contexts and requirements, thereby enhancing the applicability and relevance of the model's outcomes in various settings.

This spatial model was constructed based on four criteria: proximity to PAs, proximity to rivers and lakes, distance to streets and roads, and high landscape connectivity (Figure 4.2). Although the modeling approach is flexible enough to accommodate additional criteria, data availability at the city scale makes it challenging to include more criteria (Meerow and Newell, 2017). However, stakeholders have recommended the inclusion of data on proximity to springs and the quality of forest fragments for future iterations of the spatial model. As data availability improves and stakeholder priorities evolve, the spatial model can be iteratively updated to incorporate additional criteria and provide more comprehensive insights into urban landscape planning and conservation efforts.

This study represents a significant step forward in the implementation of nature-based solutions to address urban challenges in a highly urbanized city within the Atlantic Forest. The adoption of green infrastructure offers numerous ecosystem benefits that extend across generations. These include improvements in water and air quality, enhanced scenic landscapes, and mitigation of flooding and other natural hazards. Additionally, such initiatives contribute to the overall social wellbeing of communities by providing spaces for recreation, relaxation, and interaction with nature (MEA, 2003; Guimarães *et al.*, 2021). By leveraging the ecosystem services provided by green infrastructure, cities can create more sustainable and resilient urban environments, ultimately benefiting both present and future generations.

4.5 CONCLUSION

By employing a Multicriteria Evaluation spatial model and a mixed approach incorporating literature review and participatory technique, this study successfully identified three priority classes for increasing green infrastructure in a densely urbanized municipality within the Atlantic Forest Biome. The high-priority class represents the most suitable areas for implementing new green infrastructure. These areas are characterized by their higher forest connectivity, close proximity to PAs, rivers, and lakes, as well as their greater distance from streets and roads.

The participatory technique model emphasizes the significance of stakeholder engagement in urban environmental modeling and biodiversity management within cities. The model developed in this study has the potential to be applied to other cities. It proposes crucial interventions for a sustainable approach to urban planning, aimed at preserving biodiversity and

improving the quality of life for the population. By providing valuable support for decision-making, this study facilitates the creation of a more resilient city that is in harmony with the environment.

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5 RESILIENCE OF URBAN LANDSCAPES: IDENTIFYING PRIORITY AREAS FOR GREEN INFRASTRUCTURE THROUGH MULTICRITERIA EVALUATION

Abstract

Urban centers are among the most vulnerable areas to environmental and social challenges exacerbated by population growth and climate change. Addressing these issues requires comprehensive and sustainable planning strategies to enhance urban resilience. Green infrastructure is a proven approach to providing environmental and social benefits in cities. However, due to limited resources, particularly in tropical countries like Brazil, strategic planning is essential to maximize these benefits effectively. In this context, this study aimed to identify priority areas for green infrastructure development to improve the provision of ecosystem services in urban environments. We developed a city-scale decision-support model called “Priority Areas for Green Infrastructure” (PAGI), which integrates multiple approaches, including multicriteria evaluation, literature review, and participatory technique. The PAGI model focuses on four key ecosystem services: biodiversity conservation, flood mitigation, heat mitigation, and social wellbeing. The criteria layers were derived from land use and land cover maps, hydrographic networks, digital elevation models, road networks, and other relevant spatial datasets. These layers were grouped into the four priority themes, standardized, and combined onto a single map. This composite map was then overlaid onto the official municipal-level spatial planning map to facilitate decision-making. The results demonstrated that the PAGI model effectively supports green infrastructure planning by identifying critical areas for ecosystem service enhancement. It also revealed spatial tradeoffs, such as the conflict between biodiversity conservation and heat regulation priorities, while highlighting synergies between flood and temperature regulation. The PAGI model provides urban planners with a valuable tool for guiding the strategic development of green infrastructure, increasing the urban resilience, biodiversity conservation, floods and heat mitigation, and overall quality of life for city residents.

Keywords: urban ecosystem services, spatial planning, GIS, ecosystem services, urban sustainability, urban resilience, nature-based solution.

5.1 INTRODUCTION

Population growth and climate change bring unprecedented environmental and social challenges to urban areas, where an estimated 55% of humanity lives (Meerow, 2017; UN-Habitat, 2024; United Nations, 2019). The complex urban system is constantly changing and is increasingly vulnerable to global climate and environmental changes, such as droughts, landslides, floods, heat stress, extreme rainfall, the proliferation of disease vectors, and other natural disasters (Dharmarathne et al., 2024; McPhillips et al., 2018; UNDRR, 2019). This scenario requires city planning measures to make them more resilient to the socio-environmental problems they will face worldwide with increasing frequency and intensity.

Driven by urban expansion, associated land cover changes, such as the replacement of forest cover by impervious land (such as concrete and asphalt), result in habitat loss and threats to biodiversity (Childers et al., 2019; McDonald et al., 2008; Ren et al., 2023), in the alteration of water flows (Childers et al., 2019; Stürck et al., 2014), and consequently in essential ecosystem services, which support human wellbeing and health in cities (Ouyang et al., 2016; UN-Habitat, 2025).

The provision of ecosystem services in urban areas is directly dependent on ecosystems at local and regional levels; therefore, maintaining natural environments in cities is necessary (TEEB, 2010). The degradation of natural ecosystems can result in greater economic instability and environmental risk, especially for families living in poverty in areas without adequate urban infrastructure (UN-Habitat, 2020).

Therefore, urban areas are characterized by strong interactions between social and ecological systems and face complex social and environmental challenges (Alberti, 2024; Pickett et al., 2011). On the other hand, there is the challenge of ensuring the equitable provision of ecosystem services in cities, minimizing socio-environmental problems such as floods, landslides, and contamination of water sources, and increasing air quality and the supply of leisure areas for the entire population (Dharmarathne et al., 2024; UN, 2017). Because of the interconnectedness of social and ecological systems, addressing these challenges requires an interdisciplinary approach that integrates the multiple relationships and dependencies between the two systems to make cities more resilient (Alberti, 2024; Biggs et al., 2015).

Expanding green infrastructure is the primary strategy to increase the resilience of cities and communities (Lennon & Scott, 2014; Niemelä, 2011; Zuniga-Teran et al., 2020). This approach is now recognized as a nature-based solution for adapting cities to climate change. It is supported by maximizing the benefits that nature provides to people through ecosystem services (Aghaloo et al., 2024; IUCN, 2016; TEEB, 2010). Although there is no single definition for green infrastructure, it can be understood as an interconnected network of natural

green spaces that have multiple social and ecological benefits, including improving public health, mitigating floods, reducing urban heat islands, improving air and water quality, storing carbon, and conserving habitats and species (Austin, 2014; Childers et al., 2019; Pennino et al., 2016; Rouse & Bunster-Ossa, 2013; Saleh & Weinstein, 2016; Sutton-Grier et al., 2015; Wang et al., 2024). What is included in this green infrastructure are Protected Areas, parks, squares, urban agriculture, urban forests, riparian zones, green-blue infrastructure, green roofs, rain gardens and conventional gray infrastructures combined with green infrastructures (V. Anderson et al., 2022; Choi & Kim, 2022; Corrêa et al., 2021; Dong et al., 2017; Gašparović et al., 2022; Newman et al., 2022).

These spaces also benefit the population's mental health by increasing access to green spaces and outdoor recreation areas (Tzoulas et al., 2007; UN & WHO, 2020; Whitmee et al., 2015). These benefits of green areas in cities became evident during the COVID-19 pandemic, as people unable to travel far began to enjoy using green areas close to their homes (Wheeler et al., 2020). The “Pandemic Era” demands reevaluating our relationship with nature (The Lancet Planetary Health, 2021).

Around the world, cities are actively promoting the expansion of their green infrastructure (IUCN, 2020). Research carried out in major global urban centers such as Detroit, New York, London, and Montevideo has proposed plans to increase these areas on a large scale (Apud et al., 2020; Berkooz, 2011; Hölscher et al., 2019; Meerow, 2020; Mell, 2016).

Therefore, studies that aim to reduce cities' environmental and social vulnerability and increase their resilience to climate change are essential in large Brazilian urban centers. However, to implement these plans in Brazilian cities, municipalities' budgetary limitations must be considered, and plans with an optimal cost-benefit ratio, as with green infrastructure, must be proposed. In addition to its low initial cost, it requires less ongoing maintenance than built (or gray) infrastructures, which are common in cities (Booth & Charlesworth, 2014). In this sense, identifying priority areas for increasing green infrastructure in urban centers is essential for minimizing environmental and social problems and maximizing the benefits of implementing these areas (Hansen & Pauleit, 2014).

Multicriteria Evaluation is widely used to prioritize areas based on criteria and their respective importance for the prioritization objective (Chen et al., 2015; Saaty, 1987; R. A. Valente et al., 2021). Experts or other interested parties commonly define the importance of the criteria through the participatory technique, which allows for a balanced and appropriate solution to meet the objective (Jones & Russo, 2024; R. A. Valente et al., 2017).

In the context of environmental planning, Multicriteria Evaluation has been widely used to identify priority areas for conservation (Francisco et al., 2008; R. A. Valente et al., 2017, 2021) and landscape restoration (Childers et al., 2019; Francisco et al., 2008; Oakleaf et al., 2017; Silveira et al., 2014; R. A. Valente et al., 2021; R. de O. A. Valente & Vettorazzi, 2008; Vettorazzi & Valente, 2016). Additionally, this approach has been applied to enhance green infrastructure in urban areas (Apud et al., 2020; Assumma et al., 2021; Childers et al., 2019; Kremer et al., 2016; Vilanova et al., 2024).

Although green infrastructure is characterized by its multifunctionality, in many cities, project development is usually based on a single ecosystem benefit, such as water resources (Finewood et al., 2019; Meerow & Newell, 2017; Newell et al., 2013; Niemelä, 2011). Conversely, this work was structured to use spatial planning based on Multicriteria Evaluation to maximize the provision of several ecosystem services in expanding cities' green infrastructure. As Romero-Duque et al. (2020) mention, urban studies should be based on a holistic, Multicriteria Evaluation, and participatory approach. These studies must engage with solving the various urban environmental and social issues currently related to the degradation of natural ecosystems and climate change (Romero-Duque et al., 2020).

In this study, we aimed to identify priority areas for green infrastructure development to enhance the provision of ecosystem services in urban environments. For this, we developed a city-scale decision-support model called “Priority Areas for Green Infrastructure” (PAGI), which integrates multiple approaches, including multicriteria evaluation, literature review, and participatory technique. Priority areas for green infrastructure should be identified where ecosystem services can be maximally-maximized (Meerow & Newell, 2017) to address urban key urban challenges related to biodiversity conservation, flood and heat mitigation, and social wellbeing. Our spatial model provides planners with a strategic tool to guide the development of green infrastructure in selected candidate areas, thereby strengthening urban resilience. This approach supports local biodiversity conservation, enhances the hydrological cycle, and improves overall quality of life, ultimately increasing cities' capacity to adapt to the impacts of climate change.

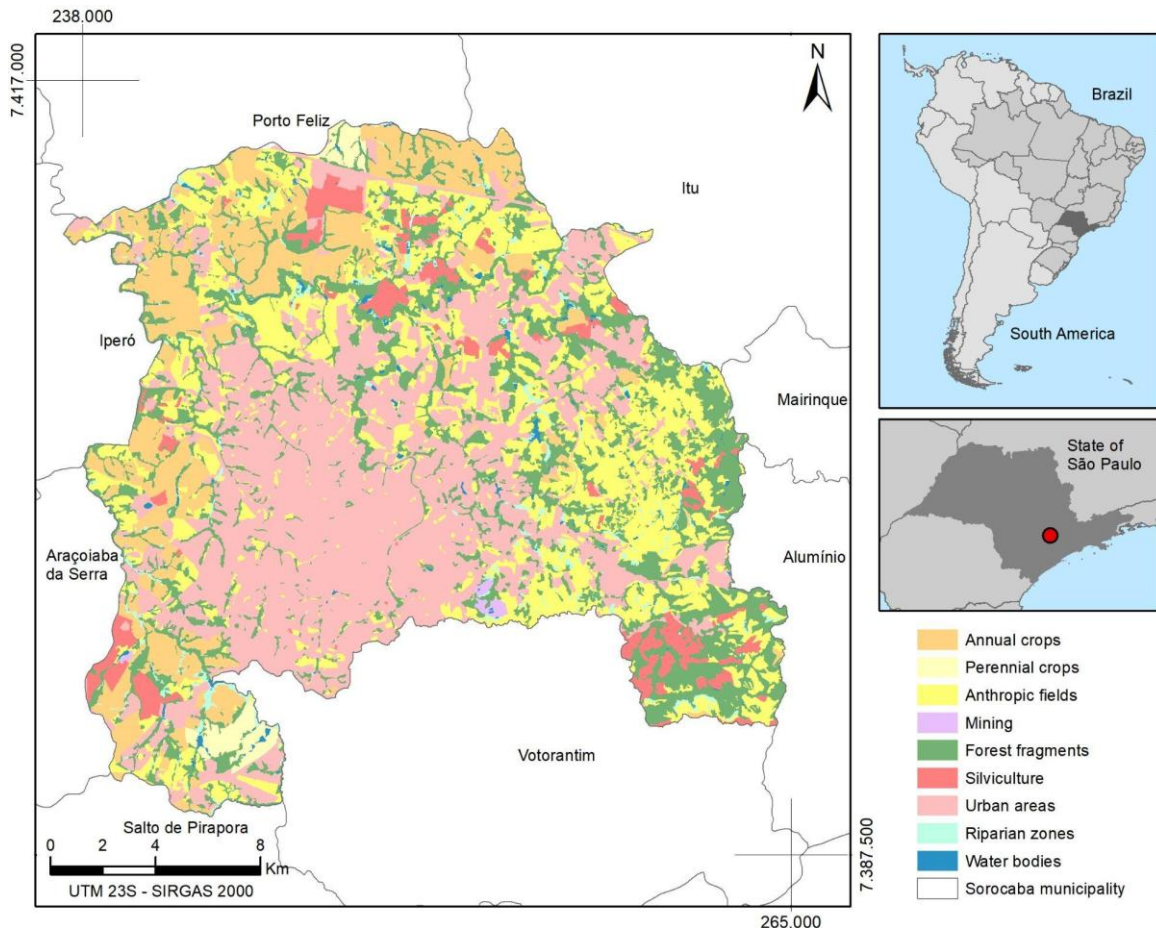
5.2 MATERIAL AND METHODS

5.2.1 Study area

Located in the southern portion of the Brazilian Atlantic Forest and the southeastern region of the São Paulo state (Figure 5.1), the study area was the Sorocaba municipality, which has a total area of approximately 45,000 ha.

The landscape is predominantly urbanized, with highly fragmented forest cover characterized by small, often poorly connected forest remnants (Mello, Toppa and Cardoso-Leite, 2016; Ribeiro, Mello and Valente, 2020). Despite this, the municipality holds significant ecological importance as it lies within a transition zone between the Atlantic Forest and the Cerrado biomes, predominantly featuring Semi-Deciduous Seasonal Forest (Montes, 2005; MapBiomias, 2019).

Figure 5.1. Sorocaba municipality, state of São Paulo, Brazil: location and land use and land cover data for 2022.



Source: Adapted from Ribeiro, Mello and Valente (2020).

In addition to its ecological importance, it has an economic importance since it is the largest urban agglomeration in the metropolitan region of Sorocaba (composed of 27 municipalities, with a total area of 11,611.48 km²), with 99% of the inhabitants living in urban

areas (EMPLASA, 2018; IBGE, 2023). Furthermore, it is close to two other large urban centers in the state of São Paulo, the metropolitan regions of Campinas and São Paulo. Economic growth and proximity to the state capital—São Paulo municipality—led Sorocaba to an intense process of converting natural areas into urban areas, reflecting the current situation of forest fragmentation. According to the Master Plan, Sorocaba has only 19.87% rural areas (Sorocaba, 2014a).

The Sorocaba River (Sorocaba and Médio Tietê sub-basin - UGRHI 10) is the city's main river. The city developed surrounding it, and nowadays, it is embedded in the urban landscape but still provides water, supports local biodiversity, and serves as a hub for leisure and cultural activities. Over the years, the Sorocaba River floodplain has undergone several watercourse rectification processes, mainly in the southern section (Martines *et al.*, 2020). These areas have been frequently flooded throughout the river's natural cycle, exposing their populations to risks (Martines *et al.*, 2020).

5.2.2 The model framework

We employed an integrated approach combining a literature review, participatory technique, and multicriteria evaluation methods to prioritize areas for green infrastructure development (Figure 5.2). Four (4) green infrastructure spatial planning model maps were created to highlight priority areas for enhancing ecosystem services, focusing on biodiversity conservation, flood mitigation, heat mitigation, and social wellbeing (Item 5.2.4).

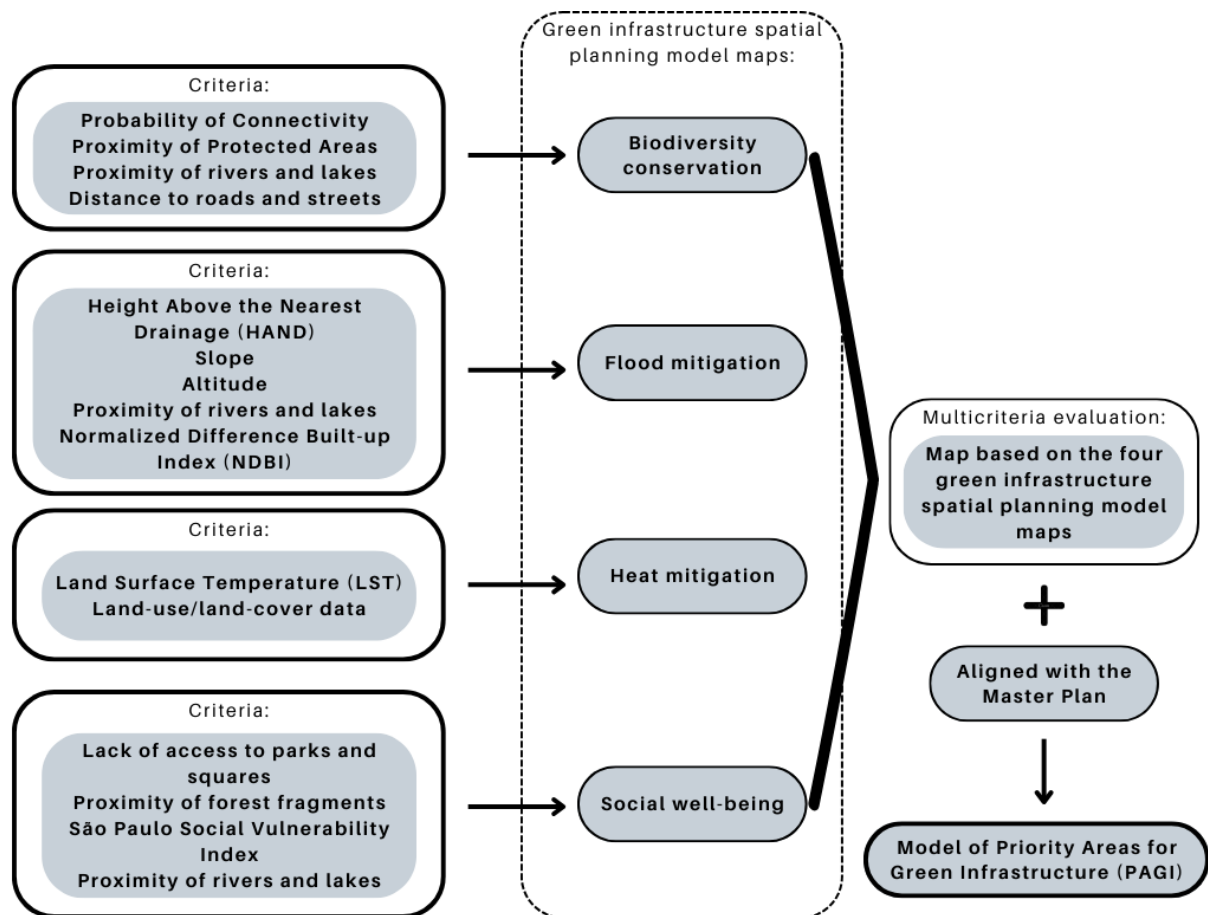
Each green infrastructure spatial planning model map followed a specific methodology (Item 5.2.4), incorporating criteria predefined through the literature review (Table 5.1), participatory technique to define the factor weights and multicriteria evaluation methods. The results for each map - biodiversity conservation, flood mitigation, heat mitigation, and social wellbeing - were presented on a continuous scale, ranging 0 to 1, with high-priority areas (values close to 1) identified as the most suitable for new green infrastructure implementation.

The subsequent steps (from 5.2.5 to 5.2.7) involved conducting a relative influence analysis for all green infrastructure spatial planning model maps (biodiversity conservation, flood mitigation, heat mitigation, and social wellbeing), followed by the aggregation of these four maps using the Weighted Linear Combination (WLC) method.

Following this, the final map - derived from the four green infrastructure spatial planning model maps - was created, with the definition of priority classes to identify potential areas for expanding green infrastructure. We then assessed the high-priority areas for green

infrastructure expansion in relation to macro-zoning maps (Master Plan) and existing green spaces.

Figure 5.2. Decision-making support model to identify priority areas for increasing green infrastructure in cities.



Source: prepared by the author.

5.2.3. Mapping criteria dataset

To establish the criteria for identifying priority areas for city-scale green infrastructure (Table 1), we conducted a comprehensive literature review using the SCOPUS and Web of Knowledge databases. This review focused on the relationships between urban areas, green infrastructure, ecosystem services, and Multicriteria Evaluation. Our search encompassed all available studies up to November 2021.

Recent research from cities such as Montevideo, New York, and Detroit provided a foundation for selecting and prioritizing the study's criteria and themes (Table 5.1) (Meerow and Newell, 2017; Meerow, 2019, 2020; Apud *et al.*, 2020; Assumma *et al.*, 2021). The set of criteria in the Multicriteria Evaluation is fundamental in the decision-making process, as they

represent the landscape's characteristics relevant to the study's primary objective (Valente et al., 2021).

The selection process for each criterion for ecosystem services prioritization themes, along with spatial attributes, data sources, processing steps, standardizations, and limitations, is detailed below (Item 5.2.4) and summarized in Table 5.1. Before setting the spatial attribute, the criteria (Table 5.1) were standardized for the study cartographic database, which had a 30 m spatial resolution, a UTM (23 S) coordinate system, and a SIRGAS 2000 datum.

Table 5.1. Criteria for defining priority areas for city-scale green infrastructure based on ecosystem services prioritization themes.

Ecosystem services prioritization theme	Criterion	Spatial attribute	Data source
Biodiversity conservation	Probability of Connectivity	Functional connectivity of landscape, considering the focal species selected for this study were Atlantic Forest birds.	Data were adapted from Ribeiro, Mello and Valente (2022). We applied the log transformation to reduce the skewness of the variable.
	Proximity of Protected Areas	Euclidean distances to Protected Areas were calculated based on their limits.	The Department of the Environment of the Sorocaba Municipality provided data on the boundaries of Protected Areas, rivers and lakes, roads, and streets.
	Proximity of rivers and lakes	Euclidean distances to rivers and lakes were calculated from drainage lines and water bodies.	
	Distance to roads and streets	Euclidean distances to roads and streets were calculated from the road layouts.	
Flood mitigation	Height Above the Nearest Drainage (HAND) data.	The HAND model results in the difference in elevation of each pixel and its nearest drainage point (Nobre <i>et al.</i> , 2016).	The authors developed the data using the 12.5 m resolution ALOS PALSAR digital elevation model (DEM) (acquisition date: 4 December 2018), which was downloaded from the Alaska Satellite Facility Distributed Active Archive Center (https://asf.alaska.edu/).
	Slope	Percent of slope	
	Elevation	Elevation in meters	
	Proximity of rivers and lakes	Euclidean distances to rivers and lakes were calculated from drainage lines and water bodies.	The Department of the Environment of the Sorocaba Municipality provided data on the rivers and lakes.

	Normalized Difference Built-up Index (NDBI)	The mean NDBI was calculated from Sentinel data obtained between January 2020 and December, normalized from 0 to 255.	Sentinel-2 image collection was obtained from Google Earth Engine in the period corresponding to January and December 2020.
Heat mitigation	Land Surface Temperature (LST) average data	Mean LST between 2020 January and April normalized ranging from 0 to 255.	LST data was obtained from Ribeiro, Menezes, <i>et al.</i> (2024) in the period corresponding to the summer season (between January and April 2020). Landsat 8 OLI/TIRS data with minimum cloud cover were selected to compose a maximum value temperature composition (Landsat crossing times are 12:00 p.m. and 1:00 p.m. for the OLI sensor).
	Land-use/land-cover data	2020 Land-use/land-cover data	Data was accessed from the MapBiomas project (Souza <i>et al.</i> , 2020).
Social wellbeing	São Paulo Social Vulnerability Index (IPVS)	The São Paulo Social Vulnerability Index data was adapted by applying the natural neighbor kriging algorithm.	Data was accessed on Sao Paulo's State Government website (http://ipvs.seade.gov.br/view/index.php)
	Lack of access to parks and squares	Ratio of the population density within a radius of 500 meters from the boundaries of urban parks and squares.	We used the national address file for statistics from IBGE (2023) for the population density and boundaries for parks and squares from the Department of the Environment of the Sorocaba Municipality.
	Proximity of rivers and lakes	Euclidean distances to rivers and lakes were calculated from drainage lines and water bodies.	The Department of the Environment of the Sorocaba Municipality provided data on the rivers and lakes.
	Proximity of forest fragments	Euclidean distances to forest fragments.	Forest fragment data from 2020 for Sorocaba were obtained from the MapBiomas project (Souza <i>et al.</i> , 2020)

Source: prepared by the author.

For the model of Priority Areas for Green Infrastructure (PAGI) validation, we utilized boundaries of urban parks and squares (Table 5.1), the macro zoning land use, and the land-use/land-cover data adapted from Ribeiro, Mello and Valente (2020). The macro zoning land

use was obtained from the Department of the Environment of the Sorocaba Municipality. It is divided into four class levels for land use change policies: (1) minor restrictions, (2) moderated restrictions, (3) high restrictions, and (4) very-high restrictions (areas for conservation) (Sorocaba, 2014b).

5.2.4 Green infrastructure spatial planning model maps focusing on biodiversity conservation, flood mitigation, heat mitigation, and social wellbeing.

5.2.4.1 Priority areas for biodiversity conservation

This model, published in Ribeiro, Mello, *et al.* (2024) was based on a Multicriteria Evaluation and a mixed approach to defining the criteria, integrating a literature review, and using participatory technique. Four (4) criteria (Table 5.1 - Figure 5.3) were used: landscape connectivity, proximity to Protected Areas, rivers and lakes, and distances from streets and roads, which were standardized to 0 - 1 using the linear fuzzy membership function (Malczewski *et al.*, 2003).

Landscape connectivity and distances from streets and roads were modeled using a linear increasing function, which assigns higher membership values as the input increases, ranging from 0 to 1 (Figures 5.3C and 5.3D). Conversely, proximity to Protected Areas, rivers, and lakes were modeled using a linear decreasing function, where membership values decrease as the input increases, starting at 1 and decreasing linearly to 0 (Figures 5.3A and 5.3B).

The Weighted Linear Combination (WLC) method (Voogd, 1982) was used to aggregate criteria (Eq. 5.1).

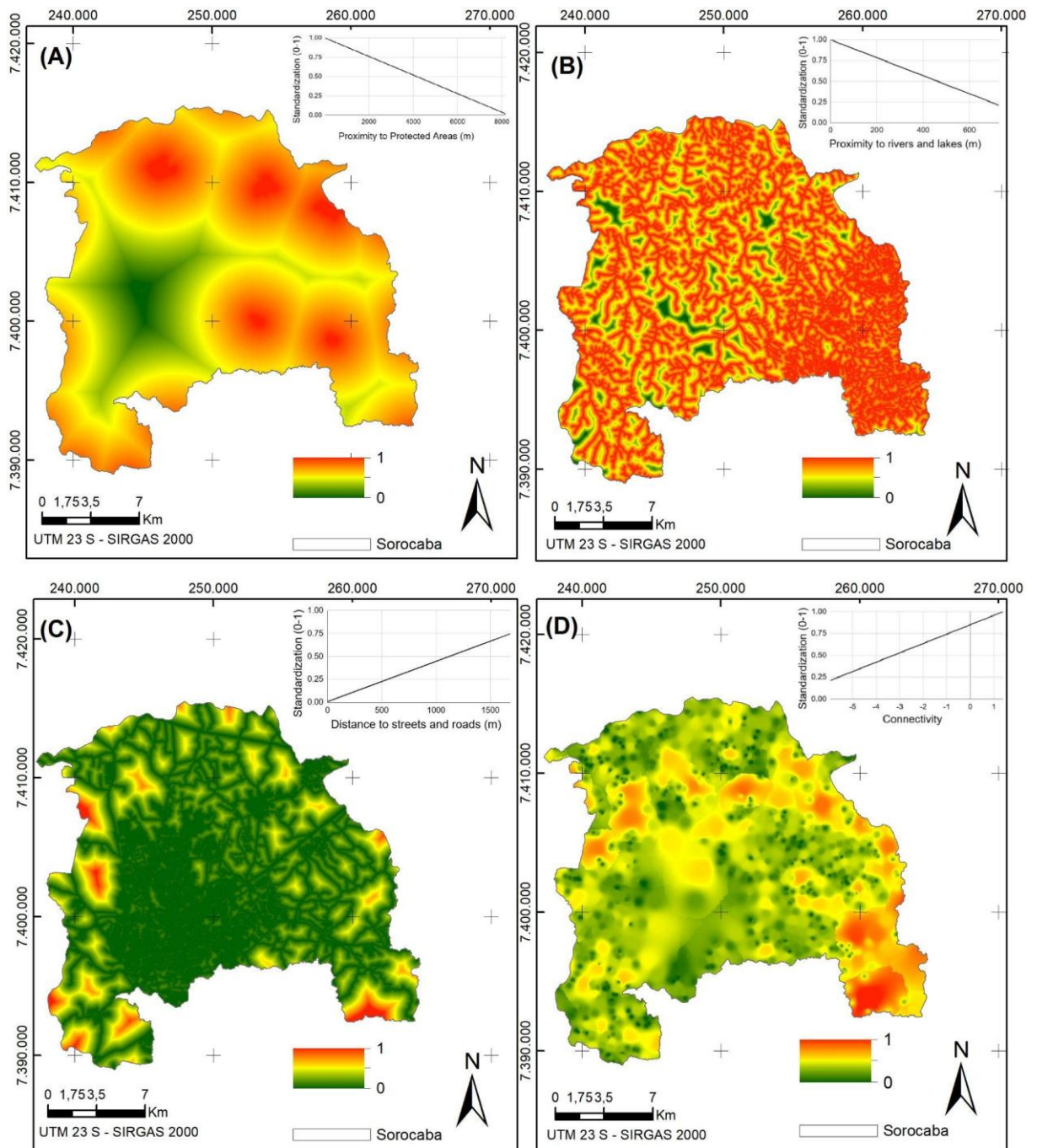
$$S = \sum w_i x_i \quad (\text{Eq. 5.1})$$

where: S is suitability; w_i is the weight of factor i; and x_i is the criterion score of factor i (Drobne and Lisec, 2009).

The resulting map, adapted from Ribeiro, Mello *et al.* (2024), was presented on a continuous scale (0 – 1), indicating varying priorities for the allocation of new green infrastructure to enhance biodiversity sites within the Sorocaba municipality. Areas with the highest priority for green infrastructure implementation corresponded to the highest values, approaching 1.

Figure 5.3. Standardized suitability and functions used for its normalization on the standard scale (0 - 1) for (A) proximity to Protected Areas, (B) proximity to rivers and lakes, (C)

distance to streets and roads, and (D) connectivity of the landscape for the Municipality of Sorocaba, State of São Paulo, Brazil.



Source: Adapted from Ribeiro, Mello, *et al.* (2024)

5.2.4.2 Priority areas for flood mitigation

This map aimed to identify priority areas for increasing green infrastructure to mitigate flooding in urban landscapes. The model was based on Multicriteria Evaluation and literature review.

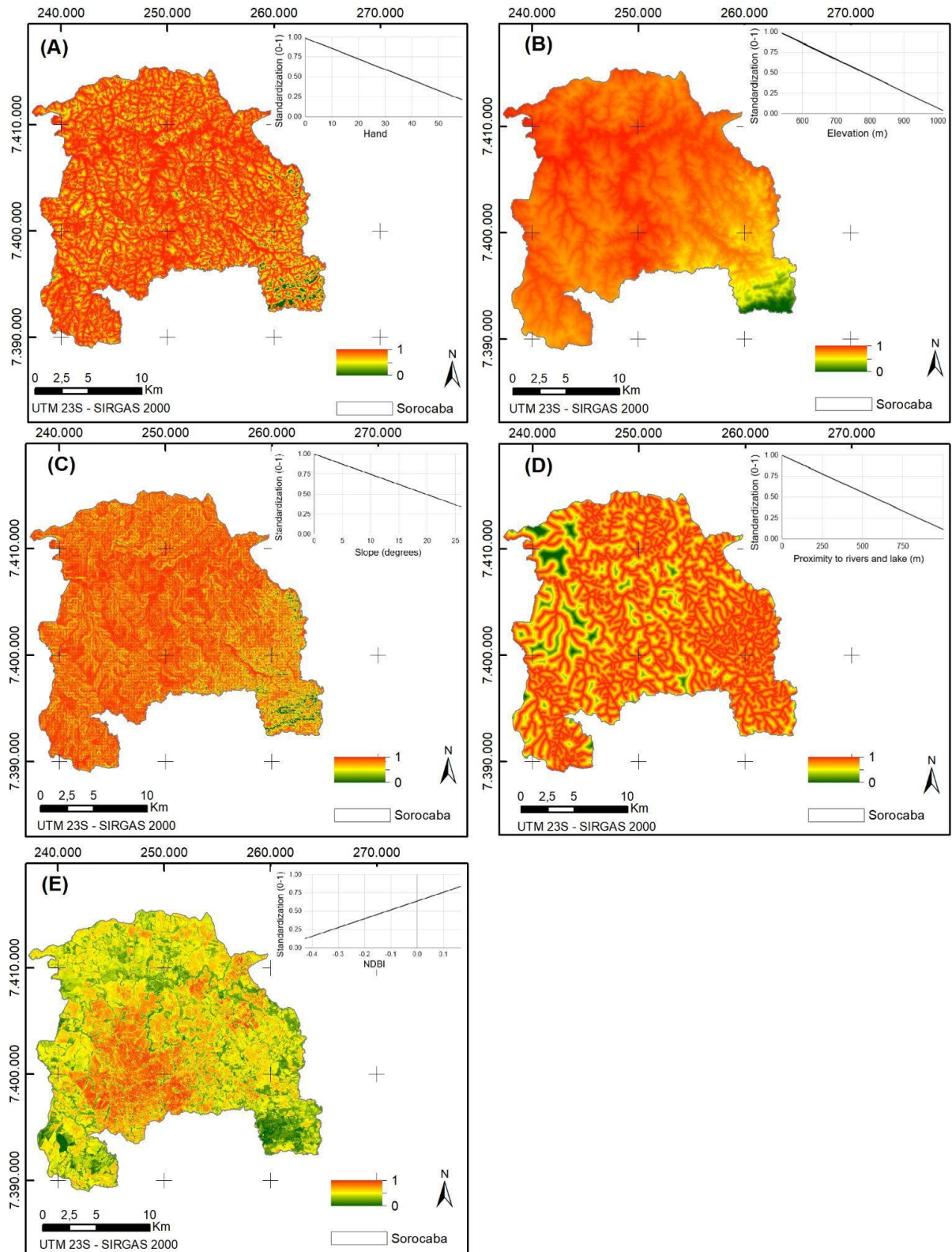
The map production for Sorocaba was approached using a set of contributing factors arranged into two groups: susceptibility and impact. Using the Weighted Linear Combination, we combined five (5) criteria, four as susceptibility and one as impact (Table 5.1 - Figure 5.4). The susceptibility was based on HAND model values (Nobre *et al.*, 2016), elevation, slope, and proximity to rivers and lakes. The impact was the Normalized Difference Built-up Index (NDBI). Susceptibility factors are related to the city's geomorphology, indicating its proneness to floods. The impact category included aspects concerning the presence of impervious surfaces (made of concrete and asphalt), once the location of this urban infrastructure can influence flood processes (Du *et al.*, 2015).

Although the quality of the data sources varied depending on their nature, they were all resampled to obtain the final possible resolution and allow for accurate aggregation. Thus, these criteria were standardized to 0 - 1 using the linear fuzzy membership function (Figure 5.4) (Malczewski *et al.*, 2003).

Normalized Difference Built-up Index (NDBI) was modeled using a linear increasing function, which assigns higher membership values as the input increases, ranging from 0 to 1 (Figure 5.4E). Conversely, HAND model values, elevation, slope, and proximity to rivers and lakes were modeled using a linear decreasing function, where membership values decrease as the input increases, starting at 1 and decreasing linearly to 0 (from Figure 5.4A to 5.4D).

We assumed that all analyzed criteria were equally important to the model and implemented a process to neutralize their influence by individually analyzing each criterion's impact using statistical parameters such as mean (μ), standard deviation (σ), and variance (σ^2). The assessment of relative influence played a crucial role in assigning Factor Weights. Standardized maps (scale 0 – 1) with higher mean values tend to have a greater impact on the results. If left unadjusted, these maps could dominate the decision-making process, leading to biased prioritization. To prevent this, appropriate Factor Weights were assigned to regulate their influence, ensuring a more balanced integration of criteria (Malczewski *et al.*, 2003).

Figure 5.4 Standardized criteria and functions used for its normalization on the standard scale (0 - 1) for HAND Model values (A), elevation (B), slope (C), and proximity to rivers and lakes (D), and Normalized Difference Built-up Index (NDBI) (E) for the Municipality of Sorocaba, State of São Paulo, Brazil.



Source: prepared by the author.

Different Factor Weights were applied to the maps, ensuring that the final weight of each map depended on the number of maps included in the analysis and the relative influence

of each spatially explicit map (Floridi *et al.*, 2011). For instance, in this model - where five criteria were analyzed - the Factor Weight for the slope criterion was 0.1119, while for the Normalized Difference Built-up Index (NDBI), it was 0.2168 (Table 5.2).

Table 5.2 The Factor Weights resulting from neutralizing the influence process.

HAND	elevation	slope	proximity to rivers and lakes	Normalized Difference Built-up Inde (NDBI)
0.1233	0.4255	0.1119	0.1223	0.2168

The WLC method (Eq. 5.1) was used to aggregate the criteria (Voogd, 1982).

For the validation, we used the ground truth points of floods in 2022 and 2023, which were kindly provided by the Urban Security Secretariat - Municipal Coordination of Protection and Civil Defense of Sorocaba. This record primarily focused on the Summer Plan period, which covers December to March. The data was provided on August 10, 2023, as documented in Administrative Process No. 18468/2023.

The priority areas for increasing green infrastructure map to mitigate flooding final result was organized on a continuous scale, ranging from 0 to 1, where the high-priority areas (nearly 1) were identified as the most suitable for implementing new green infrastructure.

Additionally, to gain a deeper understanding of citizen perceptions and enrich the discussion on floods, we utilized a participatory approach by consulting the residents of Sorocaba through an electronic form approved by the UFSCar Ethics Committee (CAAE: 53408421.9.0000.5504) to improve the research about green infrastructure spatial planning model maps focusing on flood mitigation (Access the form here: <https://zcpw9yd4wxh.typeform.com/to/FaPxmMJm>). In this form, we consulted the citizens about flood occurrences and their consequences in their lives. The methodology used here is "citizen science" because it involves collaboration between the population and scientists to map flooding points based on reports from those who experience the problems (Bonney *et al.*, 2016).

5.2.4.3 Priority areas for heat mitigation

This map aimed to identify priority areas for increasing green infrastructure to mitigate extreme temperatures in urban landscapes. For this, we used the land surface temperature from Ribeiro, Menezes, *et al.* (2024) for 2020 and the land use land cover data from the MapBiomass project (Souza *et al.*, 2020). We adapted the index developed by Schwarz, Bauer and Haase

(2011), where each land use in the landscape shows the differences in thermal emissions when compared with forest fragments. We named the green infrastructure index (GII) (Eq. 5.2).

$$GII = \left(\left(\frac{LST(i)}{LST_{(forest\ formation)}} \right) * 100 \right) - 100 \quad (\text{Eq. 5.2})$$

where LST(i) = land surface temperature data for each pixel and LST_(forest formation) = land surface temperature mean for forest formation.

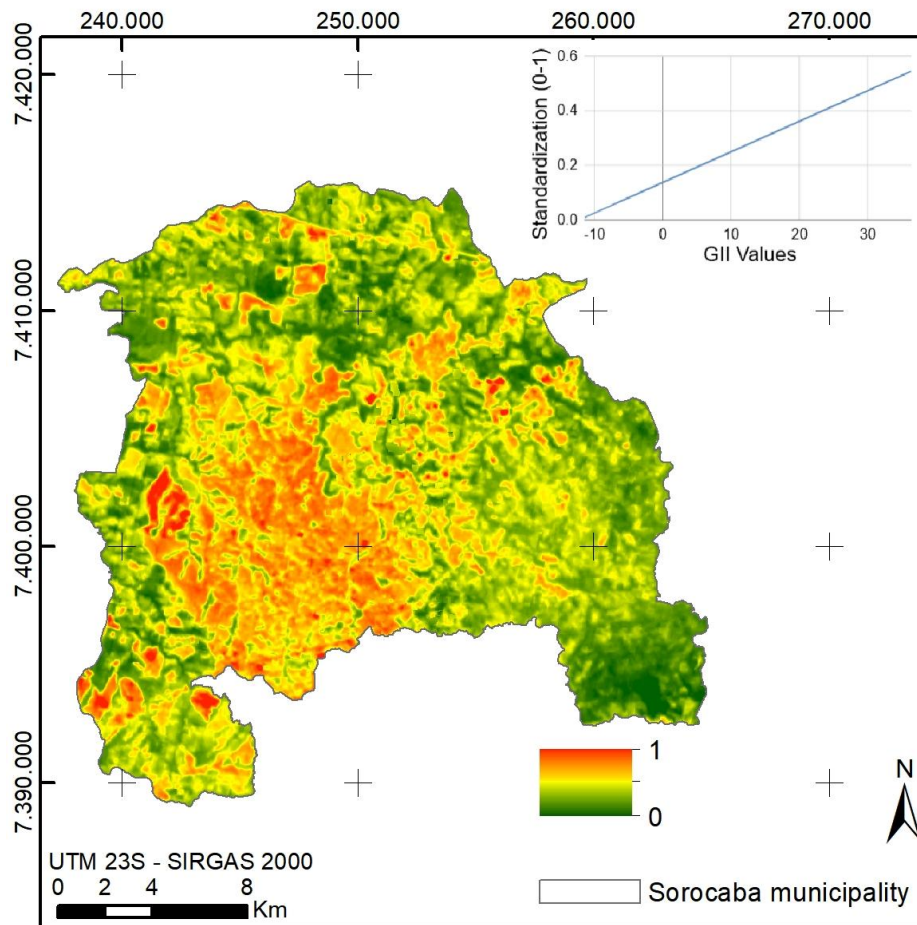
Table 5.3 summarizes the means and standard deviations (SD) of land surface temperature for all land cover classes, as well as the derived index GI values using Eq. 5.2. Higher GII values were indicated as a greater need for green infrastructure.

Table 5.3. The mean and standard deviation land surface temperature for each class and the respective GI index.

Class	LST mean (°C)	LST (SD)	Index GII mean	Index GI (SD)
Forest formation	27.85	0.93	5.73	9.32
Forest plantation	28.78	2.98	6.61	9.56
Pasture	30.03	0.92	9.66	7.34
Agriculture	28.89	1.59	11.32	10.87
Mosaic of Agriculture and Pasture	29.14	0.93	8.91	8.22
Urban areas	32.55	1.91	13.31	9.16
Rivers and lakes	28.21	1.00	7.63	9.29

The procedure involved standardizing the GII results to 0 - 1 using a linear increasing function, which assigns higher membership values as the input increases, ranging from 0 to 1 (Figure 5.5) (Malczewski *et al.*, 2003). The highest priority areas for implementing new green infrastructure are associated with the highest values (close to 1) on the standard scale from 0 to 1.

Figure 5.5 Standardized criterion and function used for normalization on the standard scale (0 - 1) for green infrastructure index (GII) for the Municipality of Sorocaba, State of São Paulo, Brazil.



Source: prepared by the author.

5.2.4.4 Priority areas for social wellbeing

This map aimed to identify priority areas for increasing green infrastructure to improve social wellbeing in urban centers. The model was based on Multicriteria Evaluation and a mixed approach to defining the criteria - integrating literature review and participatory technique.

The participatory technique involved consulting the Sorocaba population using an electronic form approved by the UFSCar Ethics Committee (CAAE: 53408421.9.0000.5504). We invite the population to rethink the urban green infrastructure for human wellbeing and, with this help, guide the project to select new areas for implementing green infrastructure in the municipality of Sorocaba, aiming at the population's wellbeing (Access the form here: [O Verde e o Bem estar humano \(typeform.com\)](https://www.typeform.com)). To this end, 152 Sorocaba citizens evaluated the criteria through electronic forms, using the Analytical Hierarchy Process based on a scale ranging from 1 to 9 points.

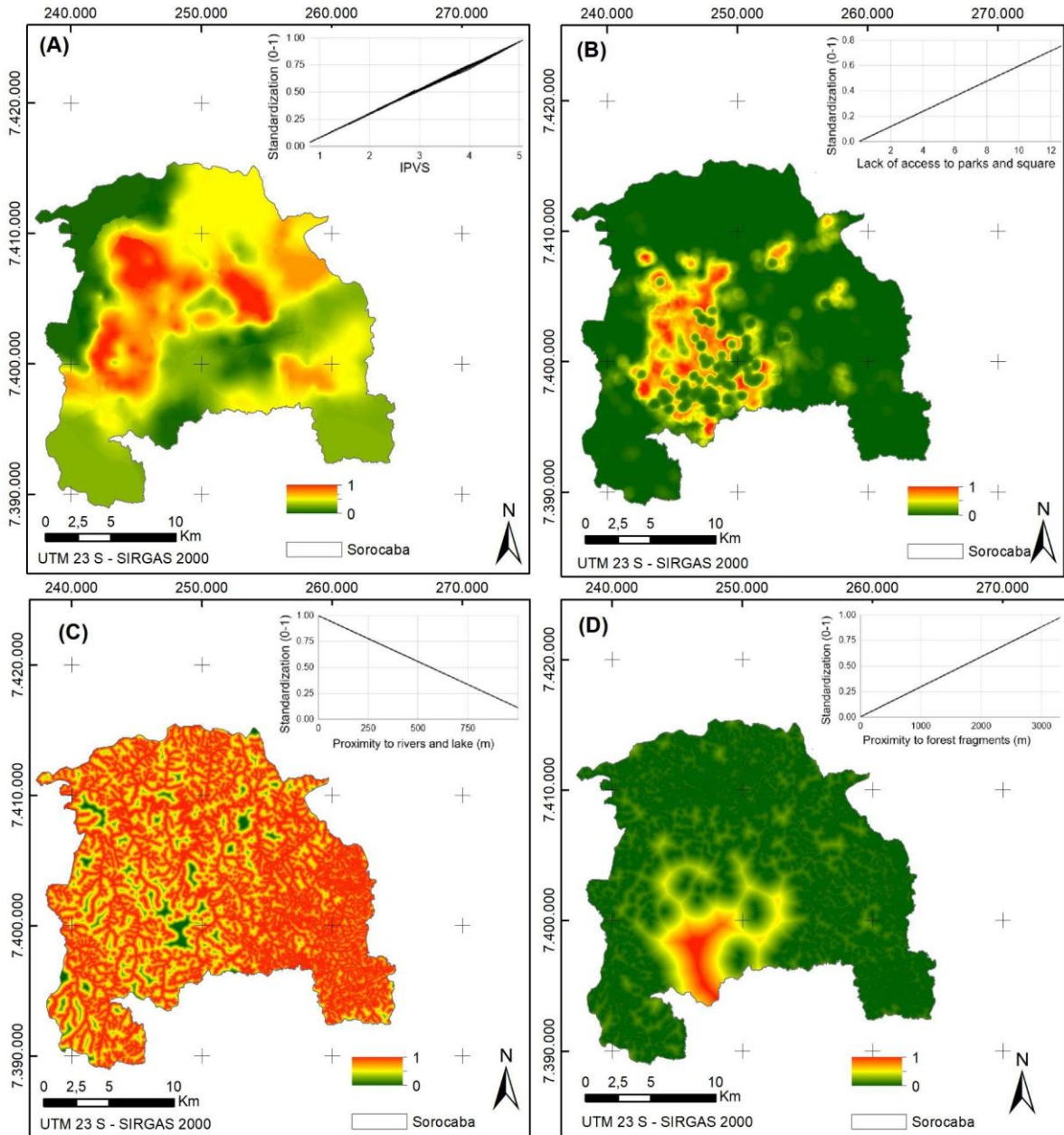
The Analytical Hierarchy Process values supported the creation of the paired comparison matrix, which was implemented in a Python script for this study (bit.ly/3ELTBFN).

The model was based on four criteria: social vulnerability, lack of access to parks and squares, proximity of rivers and lakes, and proximity to forest fragments (Table 5.1 - Figure 5.6), which were standardized to 0 - 1 using the linear fuzzy membership function (Malczewski *et al.*, 2003).

São Paulo Social Vulnerability Index (IPVS), lack of access to parks and squares and distance to forest fragments were modeled using a linear increasing function, which assigns higher membership values as the input increases, ranging from 0 to 1 (Figures 5.6A, 5.6B and 5.6D). Conversely, proximity to rivers and lakes was modeled using a linear decreasing function, where membership values decrease as the input increases, starting at 1 and decreasing linearly to 0 (Figure 5.6C).

It is important to highlight that this model does not consider private green areas within gated communities, as such information is not included in the official data provided by the Department of the Environment of the Sorocaba Municipality.

Figure 5.6 Standardized criteria and functions used for its normalization on the standard scale (0 - 1) for São Paulo Social Vulnerability Index (IPVS), lack of access to parks and squares, proximity of rivers and lakes, and distance to forest fragments for the Municipality of Sorocaba, State of São Paulo, Brazil.



Source: prepared by the author.

The paired comparison matrix enabled the calculation of Factor Weights (Table 5.4) and reached a consistency rate of 0.09175, which is within an appropriate range, according to Malczewski et al. (2003). These Factor Weights (Table 5.4) represent the relative importance of each criterion under consideration as perceived by the Sorocaba population through the participatory technique. The WLC method (Eq. 5.1) was used to aggregate the criteria (Voogd, 1982).

Table 5.4 The Factor Weights resulting from Analytical Hierarchy Process (AHP).

Social vulnerability	Lack of access to parks and squares	Proximity of rivers and lakes	Proximity to forest fragments
0.607	0.205	0.118	0.07

The resulting map highlighted a continuous scale (0 - 1) associated with different priorities for allocating new green infrastructure to improve social wellbeing in Sorocaba municipality, where the highest priority areas for implementing new green infrastructure are associated with the highest values (close to 1).

5.2.5 Analysis of the relative influence and aggregation of the four green infrastructure spatial planning model maps

After defining the four spatial planning model maps to identify priority areas for enhancing ecosystem services, with a focus on biodiversity conservation, flood mitigation, heat mitigation, and social wellbeing, each map was assessed in terms of its spatially explicit relative influence. The assessment of the level of relative influence supports the assignment of Factor Weights for each map (Malczewski *et al.*, 2003). In other words, standardized maps (scale 0 - 1) that present higher mean values may be more influential. Appropriate Factor Weights that regulate their influence must be assigned to prevent these more influential maps from dominating decision-making (Malczewski *et al.*, 2003). This systematic evaluation of more influential and non-influential criteria is essential for improving decision-making processes (Ciric, Ciffroy and Charles, 2012).

To achieve this, 3,000 sample points were established in the municipality of Sorocaba. The Zonal Statistics tool in ArcGIS 10.6 was used to extract values related to each standardized map (ESRI, Inc., Redlands, CA, USA). A normality test was conducted on the sample points, revealing a deviation from the normality assumption ($p < 0.001$). Subsequently, Spearman's correlation coefficient was employed to analyze the correlations between the maps. All the statistical analyses were conducted in Jamovi software (<https://www.jamovi.org/>).

In this map group, the relative influence of the maps' spatially explicit levels was determined after comparing the value from 3,000 points of each map through a boxplot model and main statistical parameters such as mean (μ), standard deviation (σ), and variance (σ^2).

We assumed that all four maps were equally important for the model and, based on these statistical parameters, implemented a process to neutralize their influence, ensuring that no single map disproportionately affected the results. To achieve this, we determined each map's

weighting values (Factor Weights), adjusting the final weight based on the number of maps included in the analysis and their relative influence, following the same procedures detailed in Item 5.2.4.2: Priority Areas for Flood Mitigation. This approach enabled a balanced integration of maps, preventing any single map from unduly shaping the outcomes.

Subsequently, the four maps - biodiversity conservation, flood mitigation, heat mitigation, and social wellbeing - were aggregated using the WLC method (Eq. 5.1) (Voogd, 1982).

Finally, and most importantly, we evaluated this scenario's robustness developed by neutralizing factor weights. We compared the scenarios developed with neutralizing Factor Weights with another using equal Factor Weights. We used equal Factor Weights for all maps (biodiversity conservation, flood mitigation, heat mitigation, and social wellbeing), ensuring that each map's magnitude of influence can be manifested in the decision-making support model. As a result, we ended up with a rather robust PAGI model for Sorocaba.

5.2.6 Definition of priority classes to identify potential areas for increasing green infrastructure

In the PAGI model, ten (10) classes were associated with different priorities for allocating new green infrastructure focusing on biodiversity conservation, flood mitigation, heat mitigation, and social wellbeing in Sorocaba and were delimited according to the Natural Breaks (Jenks). The darker red areas, corresponding to the highest values (10), represent locations where the potential benefits are most needed.

5.2.7 Assessing high-priority areas for green infrastructure expansion to macro-zoning and existing green spaces

The high-priority class (darker red areas), corresponding to the highest values (10), was characterized based on land-use/land cover data (Figure 5.1) adapted from Ribeiro, Mello, and Valente (2020), through a cross-tabulation (Vettorazzi and Valente, 2016).

Additionally, we incorporated the boundaries of urban parks, squares and Protected Areas (Table 5.1), and the macro zoning land use of Sorocaba to assess whether the high-priority areas identified in the PAGI model - focused on biodiversity conservation, flood mitigation, heat mitigation, and social wellbeing - are located near existing green infrastructure and within specific macro zoning land uses. Understanding the relationship between areas

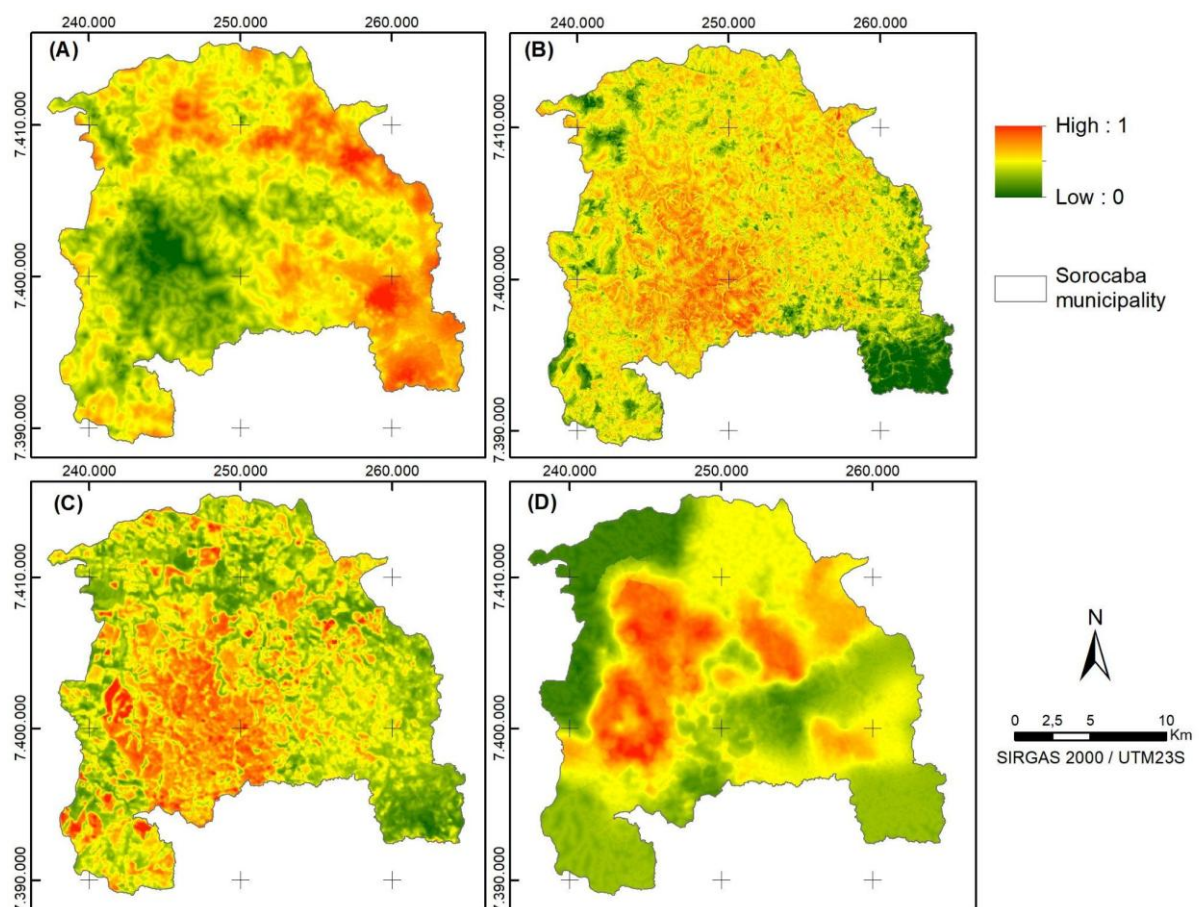
identified as potential for expanding green infrastructure and macro-zoning land use is crucial for informing urban planning and developing effective public policies.

5.3 RESULTS

5.3.1 Priority Areas for Green Infrastructure focusing on biodiversity conservation, flood mitigation, heat mitigation, and social wellbeing

The PAGI model identified biodiversity hotspots near Protected Areas with high connectivity values, close to rivers and lakes, and farther from streets and roads (Ribeiro, Mello, et al., 2024). These areas are primarily located in the eastern and southeastern parts of the city, surrounding the main rivers – the Sorocaba River and the Pirajibu-minim River (Figure 5.7A).

Figure 5.7 Green infrastructure spatial planning model maps focusing on biodiversity conservation (A), flood mitigation (B), heat mitigation (C), and social wellbeing (D) in Sorocaba, São Paulo state, Brazil. Each map shows the relative prioritization areas in Sorocaba for green infrastructure based on a commonly cited green infrastructure benefit.



Source: prepared by the author.

For flood mitigation, the model identified potential flood-prone areas characterized by low elevation, proximity to rivers, and low permeability. The incorporation of the Normalized Difference Built-up Index (NDBI) enhanced the model's precision and sensitivity by preventing the misidentification of riparian areas as suitable locations for green infrastructure, particularly where vegetation or anthropogenic fields already exist (Figure 5.7B).

When addressing heat mitigation, the model pointed to areas with the highest land surface temperatures recorded during the study period (January 2020 to April, as shown in Table 5.1). This methodology showed that extensive roofs, such as malls and industry buildings, were highlighted as the top priority areas for green infrastructure (Figure 5.7C).

Finally, in terms of social wellbeing, the model identified areas with a lack of parks and squares, particularly in neighborhoods with socially vulnerable populations. As expected, these areas were generally located farther from existing forest fragments (Figure 5.7D).

5.3.2. Analysis of the relative influence and aggregation of the four green infrastructure spatial planning maps

Although the correlations between the green infrastructure spatial planning maps are statistically relevant (p -value < 0.05), they are weak to regular correlations, according to (Callegari-Jacques, 2009), ranging from -0.572 to $+0.508$ (Table 5.5).

Table 5.5. Matrix of correlations between green infrastructure spatial planning model maps focusing on biodiversity conservation, flood mitigation, heat mitigation, and social wellbeing.

		Biodiversity	Flood	Wellbeing	Heat
Biodiversity	Rho de Spearman	—			
	p-value	—			
Flood	Rho de Spearman	-0.319^{***}	—		
	p-value	$< .001$	—		
Wellbeing	Rho de Spearman	-0.163^{***}	0.289^{***}	—	
	p-value	$< .001$	$< .001$	—	
Heat	Rho de Spearman	-0.572^{***}	0.508^{***}	0.254^{***}	—
	p-value	$< .001$	$< .001$	$< .001$	—

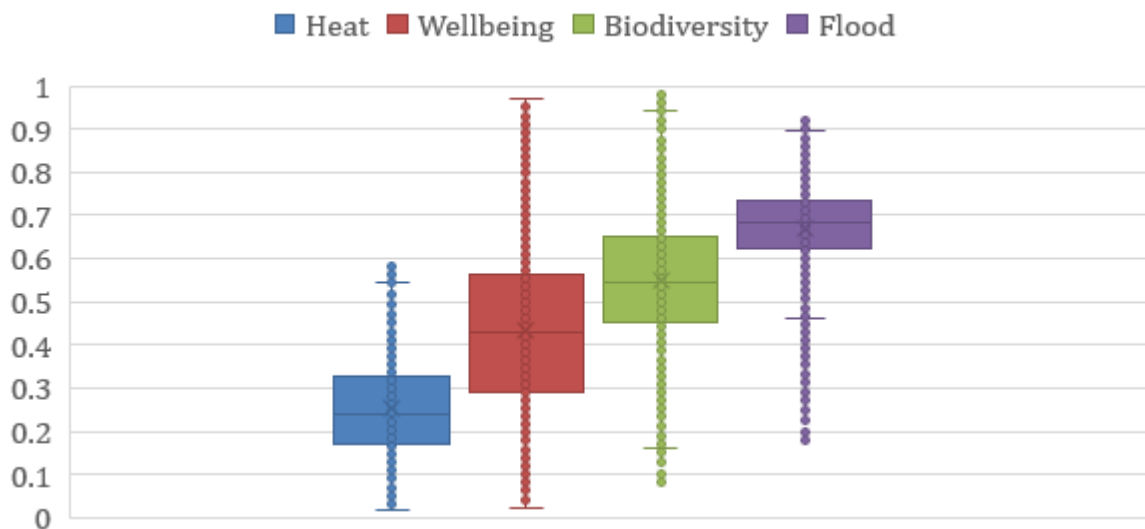
Note. * $p < .05$, ** $p < .01$, *** $p < .001$

Source: prepared by the author.

Interestingly, the biodiversity conservation map displayed a negative correlation with all maps, with the heat map showing the strongest negative correlation with the biodiversity conservation map at -0.572. Furthermore, the most significant positive correlation (+0.508) occurred between the flood map and heat. We found a positive correlation between flood, wellbeing, and heat maps.

The most influential map, that is, the one with the highest relative value, was the flood mitigation map ($\mu = 0.671$, $\sigma = 0.101$, $\sigma^2 = 14.98\%$), followed by the biodiversity conservation map ($\mu = 0.552$, $\sigma = 0.146$, $\sigma^2 = 26.50\%$), wellbeing ($\mu = 0.432$, $\sigma = 0.204$, $\sigma^2 = 47.30\%$) and finally, the heat mitigation map ($\mu = 0.252$, $\sigma = 0.101$, $\sigma^2 = 39.97\%$) (Figure 5.8).

Figure 5.8 Boxplot for green infrastructure spatial planning model maps focusing on biodiversity conservation, flood mitigation, heat mitigation, and social wellbeing.



Source: prepared by the author.

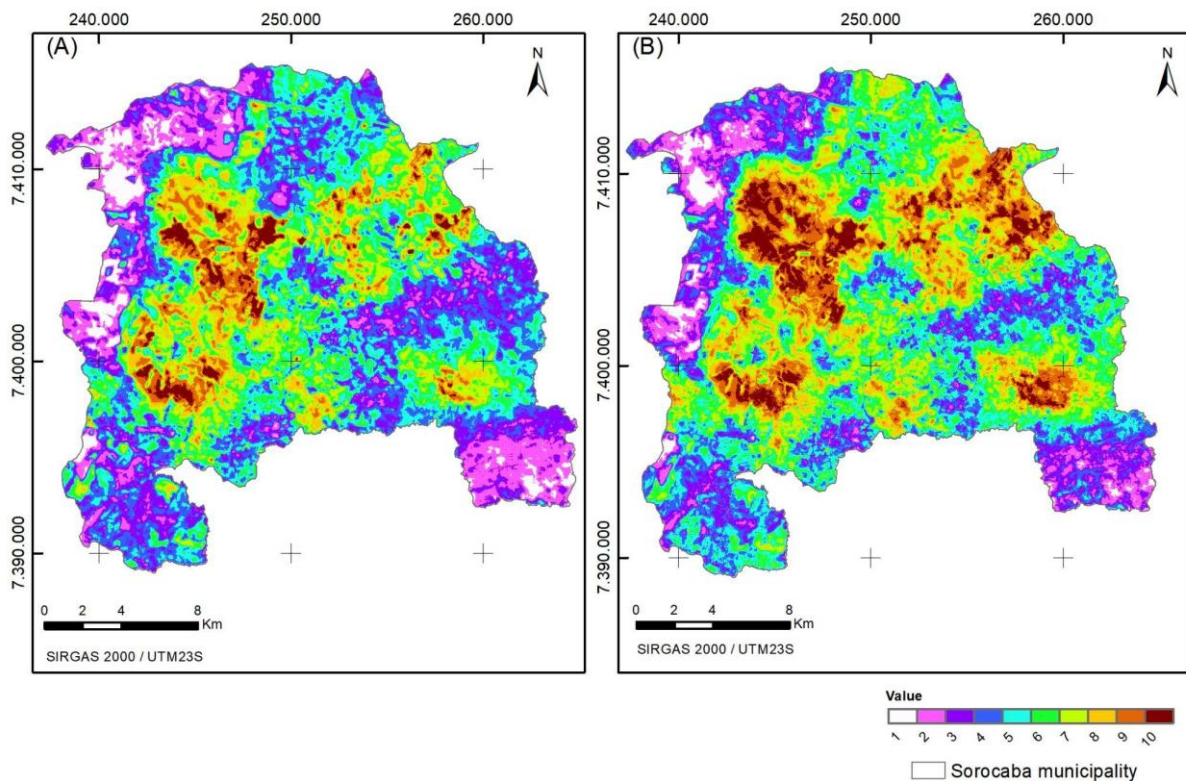
The Factor Weights (Table 5.6) represent the relative importance assigned to each map in the analysis when all green infrastructure spatial planning maps - biodiversity conservation, flood mitigation, heat mitigation, and social wellbeing - were equally important. These value adjustments were necessary to account for the influence of the maps, ensuring a balanced representation for all maps. For instance, in this scenario with four maps under analysis, the factor weight for the heat map was 0.4262, while the biodiversity conservation map weighted 0.1864 (Table 5.6).

Table 5.6 The neutralizing Factor Weights.

Heat	Wellbeing	Biodiversity	Flood
0.4262	0.2379	0.1864	0.1493

Using the Priority Areas for Green Infrastructure (PAGI) model, we identified specific high-priority ‘hotspots’ where green infrastructure is most needed in Sorocaba. As illustrated in Figure 5.9, these hotspots shift slightly depending on the scenarios considered for priority areas of green infrastructure: neutralizing Factor Weights (Figure 5.9A) or identical Factor Weights (Figure 5.9B). However, some areas, such as Sorocaba northwest and center Midwest, consistently appear to be high priorities for multifunctional green infrastructure. It is essential to highlight that the constructed PAGI model with identical Factor Weights (Figure 5.9B) - which shows the magnitude of influence of each green infrastructure spatial planning model map - identified a much larger area beyond the urban grid as a priority.

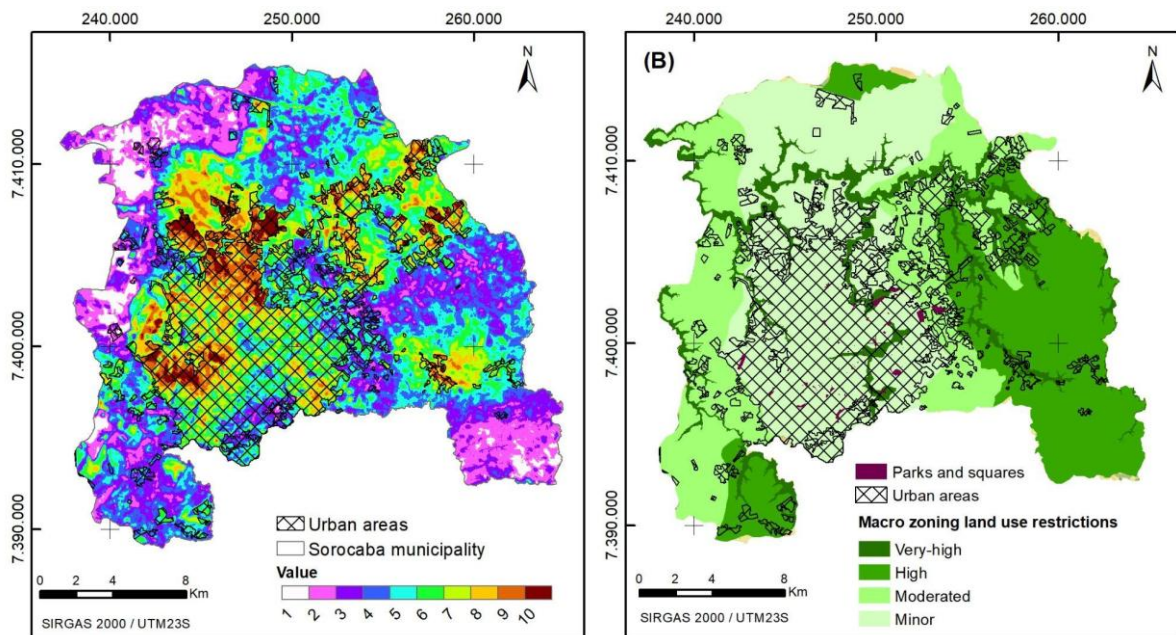
Figure 5.9. Combined Priority Areas for Green Infrastructure (PAGI) model using different weighting methods: (A) neutralizing Factor Weights and (B) identical Factor Weights for Sorocaba, São Paulo state, Brazil.



Source: prepared by the author.

On the other hand, when we neutralizing Factor Weights influence and considered the four green infrastructure spatial planning model maps equally essential, the PAGI model achieved the major top-priority areas as essential for increasing green infrastructure within the urban grid (Figure 5.10A). These priority areas are mostly within minor macro zoning land use restrictions, where physical characteristics are favorable to urbanization. Furthermore, current green infrastructure sites (parks, squares, and Protected Areas) across the city are not in high-priority geographic areas or where potential benefits of green infrastructure are needed most (Figure 5.10B).

Figure 5.10. Overlay of the Priority Areas for Green Infrastructure (PAGI) using neutralized Factor Weights and urban area grid (A) and overlay of the macro zoning land uses and the current boundaries of urban parks, squares, and Protected Areas (B) in Sorocaba, São Paulo state, Brazil.



Source: prepared by the author.

5.4 DISCUSSION

The PAGI model, created using the neutralizing factor weights model, indicates priority areas for expanding green infrastructure to maximize multiple ecosystem service benefits (Figure 5.10A). As this study illustrates, spatial tradeoffs and synergies among the ecosystem services are highlighted through positive and negative correlations in green infrastructure spatial planning maps (Table 5.5).

We found a statistically significant negative relationship between biodiversity conservation and heat mitigation maps (Table 5.5). A similar trend is observed between the biodiversity conservation map and the other maps (flood mitigation and social wellbeing), although these correlations are weak (Callegari-Jacques, 2009). Thus, restoring the priority areas for biodiversity by locating green infrastructure through more interconnected forest fragments would not be placed in locations ideal for reducing extreme temperature and stormwater or providing wellbeing for citizens and vice versa (Figure 5.7). These spatial tradeoffs indicate that achieving multifunctionality across may be challenging (Meerow and Newell, 2017). This highlights the technical-political nature of planning new green infrastructure, where tradeoffs must be understood and negotiated (Meerow and Newell, 2017). Effective planning must consider the unique needs and vulnerabilities of the municipality while also anticipating future risks, such as climate change and urbanization sprawl.

On the other hand, the green infrastructure spatial planning maps reveal potential spatial synergies across the Sorocaba municipality where green infrastructure can enhance resilience. Positive correlations are statistically significant among the flood, heat, and social wellbeing maps, principally between flood and heat (Table 5.5). Thus, even if flood concerns drive siting decisions, green infrastructure will also be located in areas suffering from extreme temperatures, mitigating both phenomena, as highlighted in other cities worldwide, such as Detroit (Meerow and Newell, 2017).

Even if the correlation between flood and social wellbeing maps is weak (Table 5.5), areas of high social vulnerability always suffer from flood impacts, which is concerning since vulnerable communities can cope less with these events (Prall *et al.*, 2024). Furthermore, a significant increase in Brazil's vulnerability to landslides and flash floods due to climate change (Debortoli *et al.*, 2017) exacerbates the challenges faced by these already disadvantaged populations.

Heat mitigation and social wellbeing maps correlation is also weak (Table 5.5); however, it is notorious that increasing temperature reduces wellbeing (Thompson *et al.*, 2023). The extreme temperature can impact wellbeing through various mechanisms, including physiological changes, such as hypertension or serotonin levels; cognitive disruptions, such as sleep disturbances; and social factors, such as increased aggression and alcohol consumption (Anderson *et al.*, 2000; Berry, Bowen and Kjellstrom, 2010; Löhmus, 2018). Furthermore, rising temperatures are especially dangerous for populations in tropical and temperate zones, as well as those in middle-income countries (Gao *et al.*, 2019), such as Brazil.

The PAGI model serves as a tool for spatial planning aimed at integrated land use management, optimizing the potential of multifunctional ecosystem services (Figure 5.10A). Multifunctional landscapes and the social benefits of green infrastructure are discussed in several works (Lennon and Scott, 2014; Mell, 2016; Apud *et al.*, 2020; Meerow, 2020; Goodspeed *et al.*, 2021). This discussion is fueled mainly by increasing concerns about climate change's far-reaching impacts (Pitman, Daniels and Ely, 2015). Green infrastructure has become preferred in contemporary landscape planning (Van Oijstaeijen, Van Passel and Cools, 2020). It offers a holistic solution that simultaneously addresses climate change, fosters social development, and enhances land economic value (Mell, 2016).

Urban green infrastructure is essential for ecosystem services, but its distribution and functionality often pose challenges. In Sorocaba, the PAGI model identifies trade-offs and synergies in these ecosystem services at the city level, revealing gaps in the current green infrastructure (Figure 5.10B). These gaps underscore the need for targeted urban planning efforts and public policies prioritizing equitable access to green spaces, biodiversity conservation, flood mitigation, and heat regulation. Addressing these challenges requires integrating ecosystem service assessments into urban planning, enhancing data accessibility, and fostering collaboration between government agencies, researchers, and local communities (Grêt-Regamey *et al.*, 2017).

The PAGI model highlights the most strategic areas for optimizing various benefits, such as flood mitigation, biodiversity conservation, temperature regulation, and social wellbeing. However, not all green infrastructure areas will equally support all the ecosystem services. This underscores the need for a well-connected network of Protected Areas, parks, urban forest fragments, and blue-green infrastructure, each designed to meet specific ecosystem service priorities. Solutions should include biodiversity-focused conservation areas, strategically planned green spaces for flood management, urban cooling zones to reduce heat stress, and public recreational areas that enhance social wellbeing. Incorporating new areas for green infrastructure into urban planning is essential for enhancing ecological connectivity and supporting biodiversity. In the context of Brazilian urban landscapes, studies have shown that urban forest fragments can act as stepping-stones, facilitating species movement and genetic flow between larger protected areas. For example, research by Ribeiro *et al.* (2022) emphasizes the role of these fragments in maintaining ecological networks within cities. By integrating these diverse approaches and creating a green, well-connected network, cities can build more resilient, multifunctional green infrastructure systems that effectively address environmental and social challenges in this Climate Change Era.

While the PAGI model helps operationalize a multifunctional resilience-based approach to spatial planning, it does not include cost or other constraints on green infrastructure development. On the other hand, the PAGI model is suited to supporting the review of Sorocaba's Master Plan or serving as a foundation for a more detailed (thorough fine-scale analysis, such as neighborhood scale, vacant lands, or streets) to identify local priority areas for green infrastructure development.

The selection of four green infrastructure spatial planning models - focusing on biodiversity conservation, flood mitigation, heat mitigation, and social wellbeing - highlights the multiple dimensions of ecosystem services that urban planning should address. However, the flexibility of the PAGI modeling approach enables the integration of additional ecosystem service maps. By broadening the range of ecosystem services considered, urban policies can more effectively address local needs and improve the resilience and sustainability of urban environments (Apud *et al.*, 2020).

Nonetheless, incorporating additional ecosystem maps depends partly on data availability, which poses a challenge at the Brazilian city scale of analysis. Access to spatial data is limited in most Brazilian territory, which comprises smaller municipalities with low institutional capacity (Barata *et al.*, 2020). For example, the Department of the Environment of the Sorocaba Municipality data reveals significant limitations in representing publicly accessible green spaces. One critical gap is the exclusion of parks and squares located within gated communities from official records, as the municipality is not responsible for managing these areas. This omission is not merely a technical issue but reflects broader socio-spatial segregation in Latin American cities (Anguelovski, Irazábal-Zurita and Connolly, 2019). Beyond restricting access, these gated communities reshape urban mobility by creating physical barriers that reinforce segregation and intensify feelings of fear and insecurity in everyday urban itineraries (Freitas and Costa, 2022). These dynamics highlight the necessity for urban policies that foster equitable access to green spaces and tackle the socio-spatial segregation of the city.

Addressing these challenges requires not only improved data accessibility but also the development of institutional capacity to support evidence-based urban planning (Fantin *et al.*, 2022). Strengthening collaborations among local governments, research institutions, and civil society can enhance data collection efforts and ensure that green infrastructure strategies are grounded in spatial and socio-environmental realities (UN-Habitat, 2020). Integrating citizen science and participatory mapping initiatives can also help bridge data gaps, particularly in under-resourced municipalities (Albagli and Iwama, 2022). Without these efforts, the potential

benefits of ecosystem service modeling may be confined to well-documented cities, reinforcing existing inequalities in access to environmental resources and climate adaptation measures (Anguelovski, Irazábal-Zurita and Connolly, 2019).

One of the following steps is to develop a website that integrates these spatial data, creating a dynamic tool for urban planning. This platform will enable real-time visualization, analysis, and decision-making based on the distribution of ecosystem services like biodiversity conservation, heat mitigation, flood control, and social well-being. Centralizing diverse datasets enhances Sorocaba municipality's capacity to implement evidence-based strategies, ensuring that green infrastructure planning is more efficient, adaptive, and responsive to environmental and social challenges.

The PAGI model can be replicated as a spatial planning approach for other Atlantic Forest Biome municipalities or even metropolitan regions in Brazil or other regions or countries. Comparing the PAGI model results across different cities, such as Sorocaba's neighboring cities and even the metropolitan region of Sorocaba, can uncover critical perceptions of the distribution of ecosystem services on a regional scale.

5.5 CONCLUSION

The PAGI model serves as a powerful tool for guiding green infrastructure planning by identifying critical areas for enhancing multiple ecosystem services. While it highlights spatial tradeoffs - such as the conflict between prioritizing biodiversity conservation and mitigating extreme temperatures - it also reveals synergies, particularly between flood mitigation and heat regulation, which contribute to strengthening urban resilience. These findings underscore the complex and social-political nature of green infrastructure planning, where tradeoffs must be carefully managed to achieve multifunctionality.

Establishing a well-connected green infrastructure network is essential for improving the multifunctionality of urban ecosystem services. This network can integrate diverse green infrastructure elements, including Protected Areas, parks, urban forest fragments, blue-green infrastructure, and nature-based solutions tailored to specific ecosystem service priorities. A connected green system would enhance ecological functions, facilitate species movement, and improve the effectiveness of climate adaptation strategies. Furthermore, ensuring accessibility and equity in the distribution of green infrastructure is vital for maximizing social benefits, especially in cities characterized by socio-spatial inequalities.

Although the model presents limitations, such as the exclusion of cost considerations and the challenge of data availability, it provides a valuable foundation for strategic urban planning, particularly in municipalities like Sorocaba.

Moreover, the Pagi model's adaptability allows it to be applied in other cities and regions. This analysis offers a comparative approach that can refine urban planning strategies on a broader scale, for example, among neighboring cities or in a metropolitan region. By optimizing green infrastructure for a significant area, cities can better address pressing environmental and social challenges, such as climate change, urban sprawl, and social vulnerability.

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6 LAND USE/LAND COVER FORECAST AND URBAN SPRAWL ANALYSIS IN A BRAZILIAN CITY IN THE ATLANTIC FOREST BIOME

Abstract

Urban sprawl, a consequence of urban growth, profoundly impacts land use/land cover, particularly in regions like the Brazilian Atlantic Forest, as this Biome hosts most of the Brazilian population and is recognized as a global biodiversity hotspot. This study uses geospatial techniques, the Cellular Automata model, and structural landscape metrics to simulate future urban land use changes for 2050. The simulation suggests a significant increase in urban areas by 2050, changing from 32.1% in 2020 to nearly 43% by 2050, mainly encroaching upon agricultural lands. Conversely, forest fragments are projected to decline (lost 3% of areas), and the connectivity analysis highlighted the loss along the rivers, emphasizing the need for proactive conservation strategies. Preserving periurban agriculture is vital for food security and sustainable development, while innovative management of riparian ecosystems enhances urban biodiversity and citizen wellbeing. Sustainable urban planning and conservation efforts are imperative to mitigate the adverse effects of urban sprawl and foster resilient cities. This research provides crucial insights for decision-makers aiming to balance urban development with environmental preservation in the face of rapid urbanization.

6.1 INTRODUCTION

Urban sprawl is a consequence of urban growth, resulting in land use and land cover changes, increased ecosystem fragmentation, and the loss of agricultural lands. These changes have significant ecological, social, and health consequences, impacting the urban environment's ecosystem services and human wellbeing (Pereira *et al.*, 2023). Habitat fragmentation, noise pollution, air pollution, reduced water quality, reduced vegetation cover and structure, and artificial light all degrade urban ecosystem services.

These multidimensional problems are critical in Brazilian cities within the Atlantic Forest, as this Biome hosts most of the Brazilian population and is recognized as a global biodiversity hotspot. Thus, forest protection, restoration efforts, and potential ecosystem services are also examined as key topics shaping the future of the Atlantic Forest Biome.

Although urban areas represent only a small percentage of the planet's terrestrial surface, they are predicted to grow by 1.2 million km² by 2030 (Seto *et al.*, 2012). Future scenario

simulation models, such as Cellular Automata, have been extensively used to simulate the effects of urban sprawl and land use changes. By integrating Cellular Automata models with geographic information system (GIS) and remotely sensed data, it becomes feasible to monitor the current conditions and forecast future spatio-temporal land use and land cover changes. This integrated approach can facilitate the analysis of environmental protection and urban sustainability initiatives, thereby enabling informed decision-making for sustainable urban development.

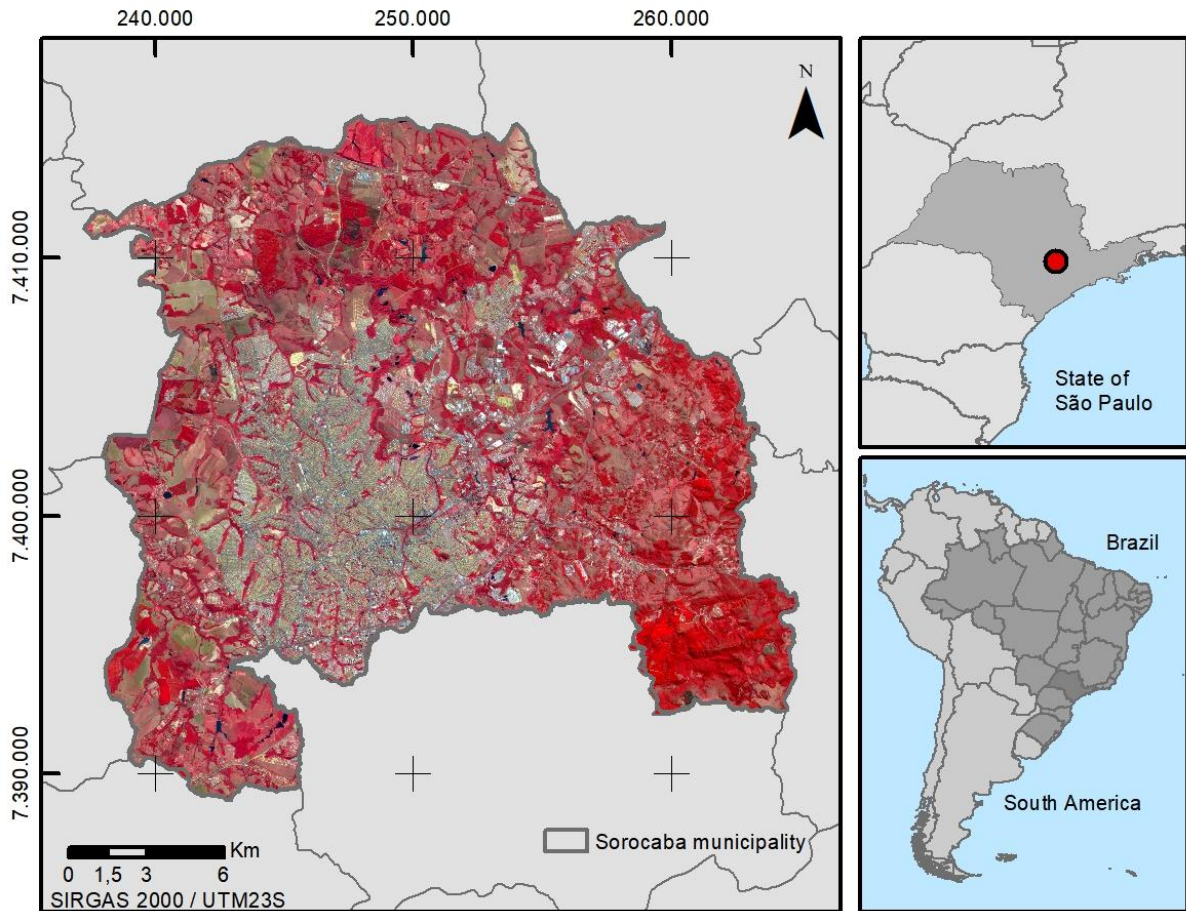
In this regard, this study uses geospatial techniques, the Cellular Automata model, and structural landscape metrics to simulate future urban land use changes for 2050. It aims to assess their impact on land use and land cover in Sorocaba municipality in the Atlantic Forest Biome. This forecasting approach can inform decision-making about environmental protection and urban sustainability initiatives offering multigenerational benefits for city dwellers.

6.2 MATERIAL AND METHODS

6.2.1 Study area

The study area is Sorocaba municipality, a typical urban landscape in the Atlantic Forest context in southwest Brazil in the São Paulo state (Figure 6.1). The municipality has 450 km² in area and a vast urban area surrounded by a highly fragmented forest composed of small fragments of Seasonally Dry Tropical Forest.

Figure 6.1 Sorocaba, state of São Paulo, Brazil. False-color composition R(NIR), G(Red), and B(Green) from CBERS-4 satellite image from 2021.



Source: prepared by the author.

The local population has grown from 586,625 in 2010 to 723,682 in 2022, making it the ninth largest in São Paulo state. Today, 99% of its residents live in urban areas.

6.2.2 Data set

The data used in this study includes land use and land cover maps from the MapBiomas project (<https://brasil.mapbiomas.org>) - accessed directly from Google Earth Engine in raster format (30-m resolution, Collection 8.0). For this study, the land use and land cover maps are classified into four classes: forest fragments, mosaic of agriculture and pasture, urban, and water.

The 12.5 m resolution ALOS PALSAR digital elevation model (DEM) data (acquisition date: 4 December 2018) was downloaded from the Alaska Satellite Facility Distributed Active Archive Center (<https://asf.alaska.edu/>) and used to generate the slope and elevation map.

Land surface temperature data was obtained from Ribeiro *et al.* (2024) in the period corresponding to the summer season (between December 2018 and March 2019). Landsat-8

images with minimum cloud cover were selected to compose a maximum value temperature composition (Landsat crossing time of 01:00 p.m. for OLI sensor), and it was normalized to a standard scale by a linear fuzzy set membership function, ranging from 0 to 255 on ArcGis software (version 11.8).

The boundaries of Protected Areas registered in the city between 2012 and 2016 were obtained from the Brazilian National Protected Areas Register (<https://www.gov.br/mma/pt-br>).

The macro zoning land use was obtained from the Department of the Environment of the Sorocaba Municipality, and it was divided into four class levels for land use change policies: very-high restrictions (areas for conservation), high restrictions, moderated restrictions, and minor restrictions.

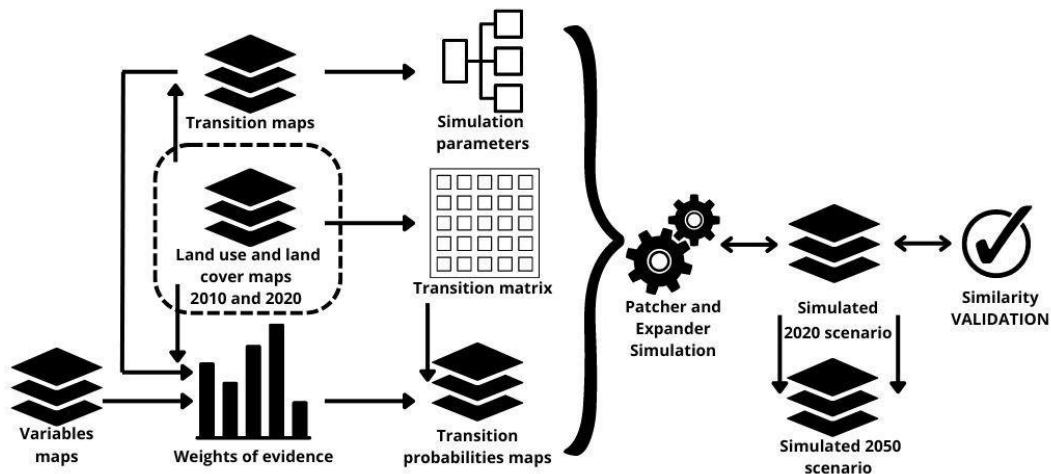
The Department of the Environment of the Sorocaba Municipality provided the vector data for roads and streets, rivers and water bodies, parks and squares, and the land use zoning of Sorocaba, all based in 2014.

6.2.3 The model

The land use and land cover future model for 2050 was simulated in DINAMICA EGO (<https://csr.ufmg.br/dinamica/>). This spatially explicit simulation model combines the concepts of Markov Chain and Cellular Automata modelling. DINAMICA EGO uses historical land use and land cover maps (2010 and 2020 from MapBiomias, in this case) and selected spatial variables organized into two cartographic subsets: dynamic and static (Soares-Filho *et al.*, 2002).

The processing steps include (Figure 6.2):

Figure 6.2 Steps used to develop the 2050 simulation scenario.



Source: prepared by the author.

(i) Calculation of the annual overall transition rate by cross-tabulating classification maps extracted from MapBiomias data in 2010 and 2020;

(ii) Calculation of the local transition rate by the weight of the evidence model. Four classes of land use and land cover and a raster with eight variables (static maps) were considered: altimetry, slope, land surface temperature, distance from rivers and water bodies, distance from roads and streets, distance to Protected Areas, land use zoning map, and distance to parks and squares. The simulated landscape maps are oriented, besides historical land use and land cover maps, through spatial transition probability maps, which depict the probability of a cell at a position (x, y) to change from state i to state j , being the i and j types of land use and land cover class - Bayesian probability-based methods. The transition probability maps were developed through weights of evidence, where weights of evidence value represent the influence of each level or distance range of each variable on the local or spatial transition probabilities;

(iii) Calibration of the model to confirm the independence between each pair of spatial variables. Cramer's coefficient (C) and joint information uncertainty (J) were used, ranging from 0 to 1, where 0 indicates independence, and 1 signifies complete correlation. When the C and J values are less than 0.5, there is no apparent correlation between the two variables;

(iv) Execution of the model (2010-2020) through a Cellular Automata rule transformation engine, which includes two complementary transformation functions: Expander and Patcher. The Expander function manages the expansion and contraction of existing patches, while the Patcher function controls the generation of new patches;

(v) The accuracy assessment of the simulated and actual observed changes using the interactive fuzzy comparison method. The similarity of simulated and actual land-use changes is compared, that is, between the 2020 current and the 2020 simulated value. The comparison is accomplished by scanning multiple-sized neighborhood windows - e.g., 3x3, 5x5, 11x11 cells - corresponding to the multiresolution goodness-of-fit approach;

(vi) Setting up and simulating the future urban sprawl scenario.

We applied the change detection analysis (intersect tools) in ArcGIS software to evaluate and quantify differences between land use and land cover from 2020 to 2050. This involves employing metrics at the class levels, including Total Area and Percentage of Landscape.

Additionally, connectivity analysis for 2020 and 2050 was conducted using the Probability of Connectivity (PC) index (Saura and Pascual-Hortal, 2007) in the Graphab software (<https://sourcesup.renater.fr/www/graphab/en/home.html>). The PC index is a global metric given by Eq. (6.1).

$$PC = \frac{\sum_{i=1}^n \cdot \sum_{j=1}^n \cdot a_i \cdot a_j \cdot p_{ij}^*}{A_L^2} \quad (\text{Eq. 6.1})$$

where p_{ij}^* is the maximum probability of movement between the parcels i and j (i.e., corresponding to the minimum cost); a_i a_j are the areas of the parcels i and j ; A_L is the total area of the study zone, and n is the number of parcels.

The probability p_{ij}^* is obtained by transforming the distance d_{ij} , between parcels i and j by an exponential function such that:

$$p_{ij}^* = e^{-\alpha d_{ij}}$$

where d_{ij} is the least-cost distance between i and j , and α expresses the intensity of decreasing probability of dispersion p resulting from the exponential function.

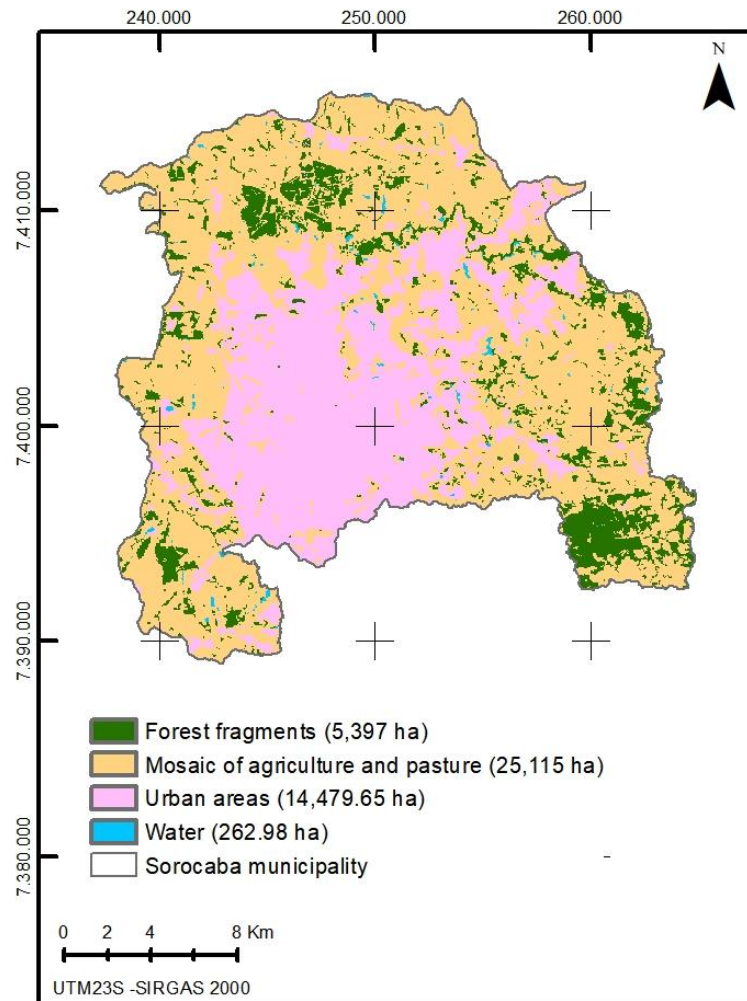
The value α was determined by $p_{ij}^* = 0.5$ when d corresponds to the median dispersal distance (for birds). Thus, the PC metric was set up at a distance (d) of 100 m, covering 50% of the dispersal events of the focal study species (i.e., Atlantic Forest birds).

The fractions were calculated from 0 to 1, and the results were multiplied by 100 to interpret the percentage. The Natural Breaks algorithm was used to classify the Probability of Connectivity (PC) on the ArcGIS software into high, medium, and low levels.

6.3 RESULTS AND DISCUSSION

The simulated land use and cover for 2020 (Figure 6.3) showed a 67% similarity with the actual landscape within an analysis window of size 5x5. This means that the simulation correctly identified the location of land use and land cover classes in more than half of the created pixels.

Figure 6.3. Land use and cover simulation for 2020 in Sorocaba, State of São Paulo, Brazil.



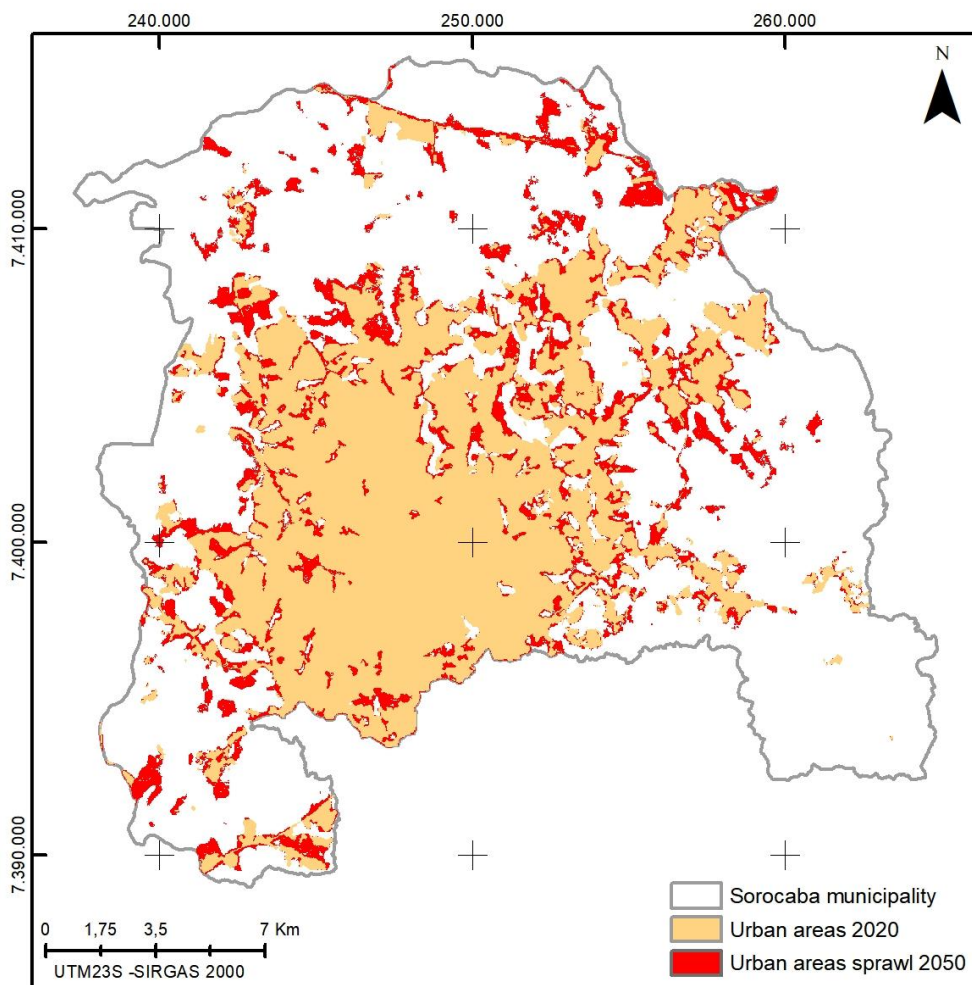
Source: prepared by the author.

These excellent results were attributed to the variables selected for this model. The correlations between variables, the C and J values, showed that all variables are critical in explaining the phenomenon, with the “land use zoning map” and “altimetry” showing the highest correlation. We tested various Patcher values, and adopted a value of 0.17 for this model.

Therefore, after calibrating the model and achieving great performance, it was deemed viable to continue simulating scenarios, as these would provide critical predictive insights for ongoing discussions.

The simulation indicates that the urban area rates will increase from 32.1% in 2020 to nearly 43% by 2050 (Figure 6.4), with most of the expansion occurring in agricultural lands and pastures (Figures 6.5 and 6.6).

Figure 6.4. Urban sprawl simulated for 2050 for Sorocaba municipality, São Paulo state, Brazil.

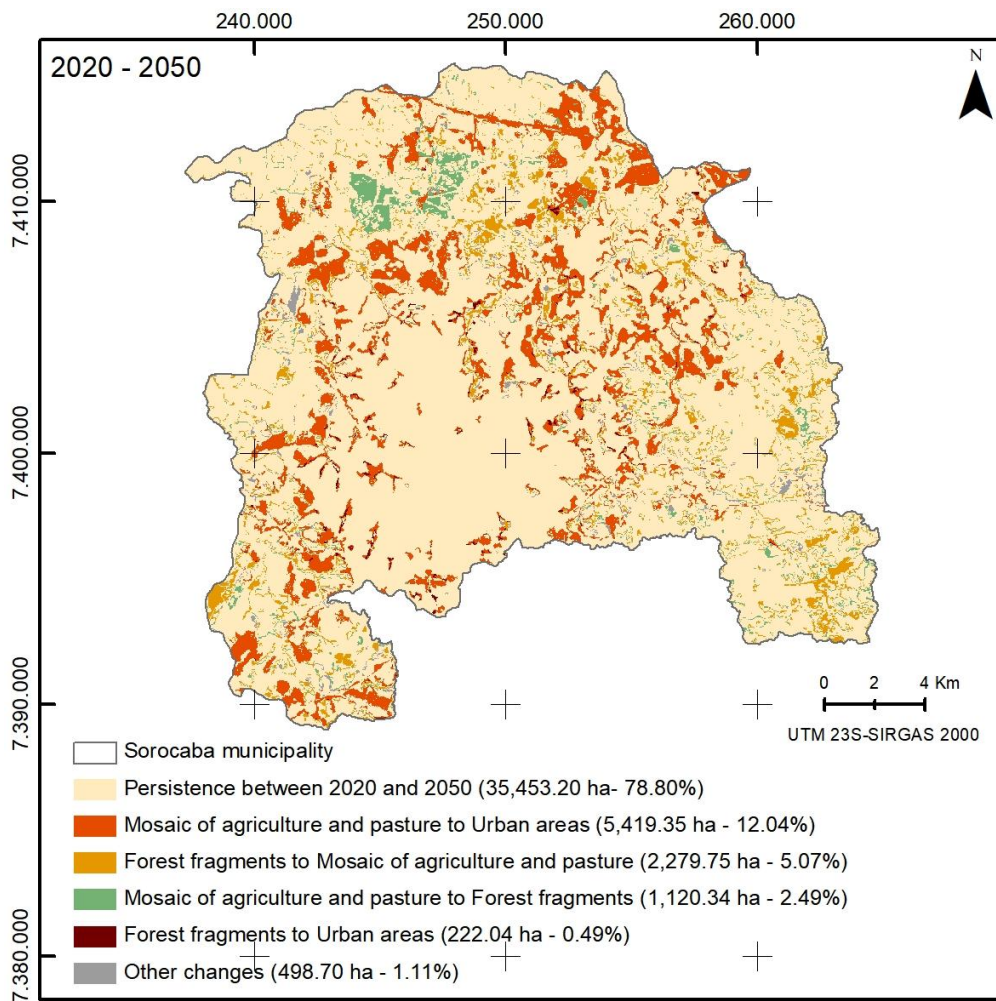


Source: prepared by the author.

The municipality's boundaries are expanding into the surrounding areas, a typical pattern of suburban sprawl (Figures 6.4 and 6.5). This pattern of urban growth contrasts with the compact city model, which aims to accommodate urban development while minimizing the consumption of undeveloped land (UN-Habitat, 2021). These undeveloped areas, often mosaics

of agriculture and pasture or forest fragments, are vital for providing ecosystem services to urban areas, such as flood mitigation and reducing urban heat islands. In this sense, this study can help the municipality's urban planning prioritize compact planning, discouraging the further sprawl of the already substantial urban limits.

Figure 6.5 Change detection map between 2020 and 2050, in Sorocaba, State of São Paulo, Brazil. The 2020 map was adapted from MapBiomias.

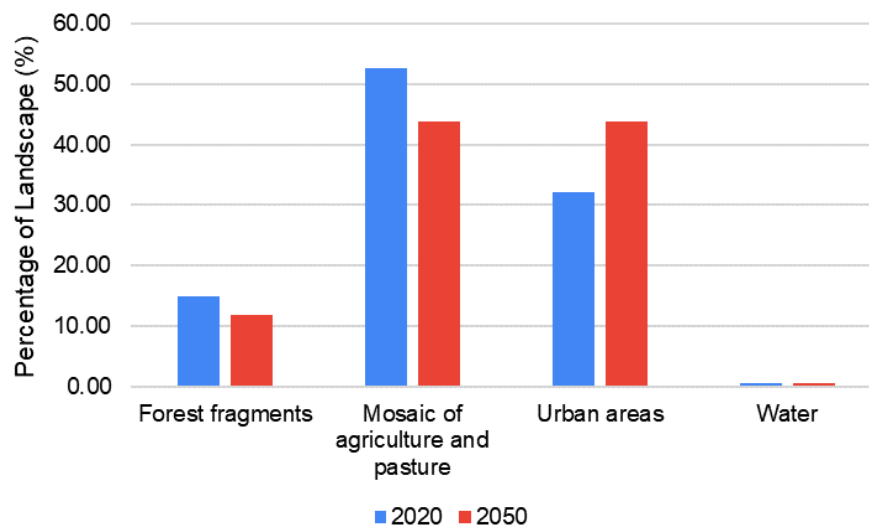


Source: prepared by the author.

Conversely, the mosaic of agriculture and pasture is projected to decrease from 52.6% in 2020 to 44% by 2050 (Figure 6.6). However, this class has the most extensive persistence area (without land use and land cover changes) in the landscape, covering nearly 17,000 ha, followed by urban areas with nearly 14,000 ha. Given the encroachment of urban sprawl, protecting agricultural land in periurban areas is crucial for limiting land use and land cover conversion, ensuring continued proximity of ecosystem service and food production to city consumers (Magoni and Colucci, 2017; UN-Habitat, 2021). Moreover, agricultural land

systems are relevant to 11 of the 17 Sustainable Development Goals (SDGs). For instance, periurban agricultural lands can help reduce poverty and improve water quality, while urban agriculture contributes to increasing urban livability and access to green spaces (e.g., urban gardens and green roofs), mitigating the impact of natural hazards and pollution, and ensuring food security. Therefore, proactive management of urban land expansion is critical for preserving agricultural lands and fostering equitable urban landscapes, especially in small and medium cities.

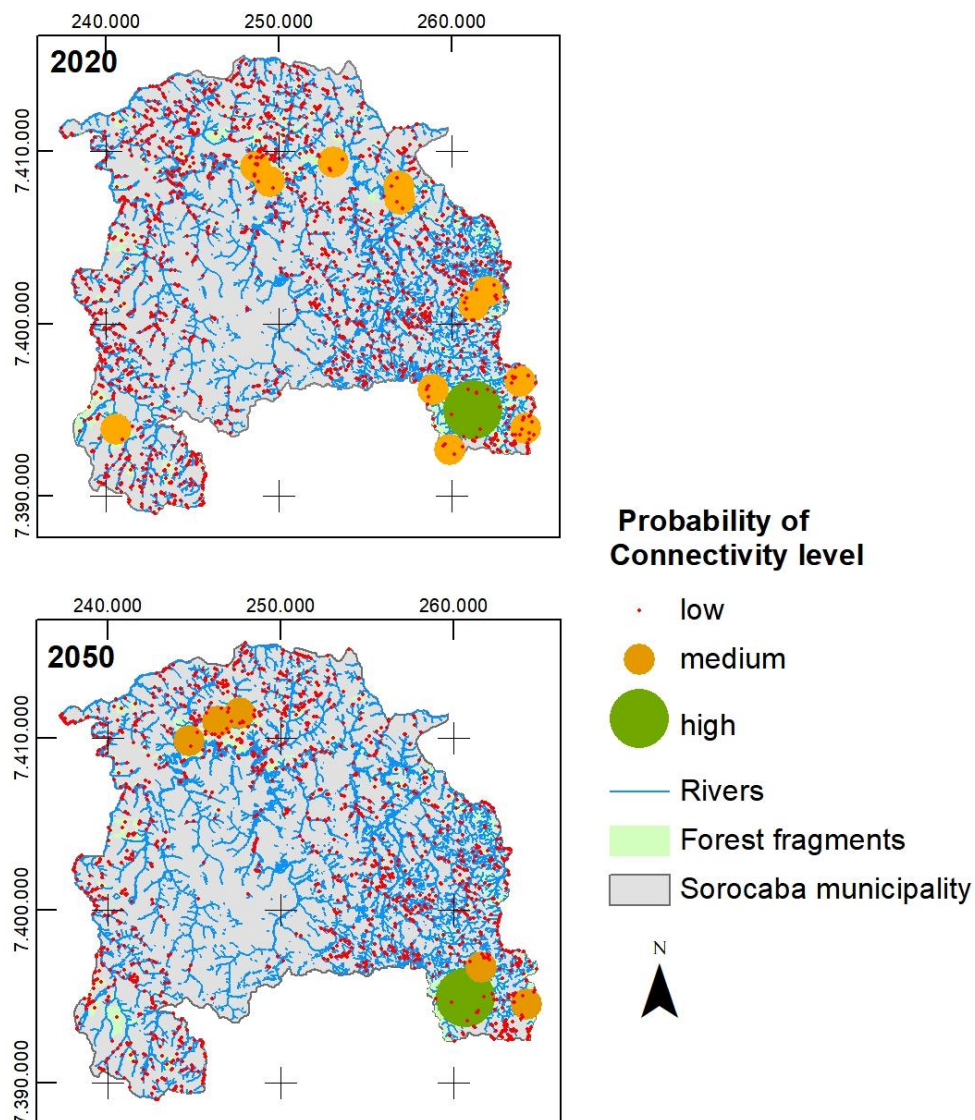
Figure 6.6 Land use/land cover changes between 2020 and 2050 for Sorocaba municipality, State of São Paulo, Brazil.



Source: prepared by the author.

In 2020, forest fragments comprised nearly 15% of the landscape, a proportion projected to decrease to 12% by 2050 (Figure 6.6). Our forecast (Figure 6.5) indicates that 5.07% of the forest fragments would convert to a mosaic of agriculture and pasture, while another 2.49% will transition to urban areas, with these changes most noticeable in the riparian areas. In 2020, the key forest fragments essential for connectivity were concentrated along Pirajibu-Mirim river, one of the main rivers in the municipality (Figure 6.7). However, by 2050, the forecast shows decline in connectivity along the rivers due to the loss of forest fragments in riparian areas. This will result in concentrated connectivity in the southwest, a region with the highest altimetry and many smaller rivers, and in the north, near the Protected area known as the Corridor of Biodiversity.

Figure 6.7 Essential forest fragments for Sorocaba municipality, State of São Paulo, Brazil, with highlighted nodes by Probability of connectivity index.



Source: prepared by the author.

Riparian ecosystems in urban environments are often degraded; however, implementing innovative management practices is crucial for conserving these ecosystems' services, which can lead to improvements in air quality, microclimate, and urban biodiversity (Veról *et al.*, 2020). In other words, sustainable management of urban riparian areas can potentially improve the health and wellbeing of the citizens. Therefore, monitoring land use sprawl and changes in urban green infrastructure, including their impact on habitat connectivity, is crucial to supporting policymakers and planners in ensuring sustainable urban development and maintaining biodiversity in the Sorocaba municipality.

Overall, global landscape connectivity would decline from 4.60% in 2020 to 2.87% in 2050. The connectivity analysis revealed that this decrease was primarily due to forest fragmentation and area loss, driven by urban expansion (Figures 6.4 and 6.6). Furthermore, most forest fragments are insufficient to support connectivity, indicating a fragmented landscape with low connectivity (Figure 6.7). We emphasize the crucial role of municipal governments in establishing urban ecological networks to foster more resilient cities. Regularly updated spatio-temporal analysis of green infrastructure, urban sprawl, and landscape connectivity analysis can offer significant ecosystem benefits to urban populations when integrated into urban planning studies.

This research on urban sprawl addresses the pressing challenge of enhancing sustainability and resilience in global urban environmental agendas, particularly in rapidly urbanizing landscapes like the Brazilian Atlantic Forest. Urban sprawl simulations are crucial for helping cities meet the Sustainable Development Goals (SDG), particularly SDG Goal 11, the New Urban Agenda (UN-Habitat, 2020) recommendations, and the United Nations campaign - Race to Resilience. These efforts aim to transform urban areas into healthy, clean, safe, and resilient to the impacts of climate change. This is especially important for developing countries such as Latin America, where cities continue to experience significant sprawl. Effective planning for these sprawls requires conserving green infrastructure and improving ecosystem services and city resilience.

Future urban expansion planning analysis offers a valuable tool for balancing future urban development and ecological conservation; however, assessing urban land sprawl is uncertain and has practical limitations. In this regard, future research must prioritize filling knowledge gaps in the theoretical framework and practical land use applications. It should also strive to enhance modeling techniques, integrate economic and political variables into simulation models, and formulate holistic urban planning strategies explicitly focusing on sustainability and resilience.

6.4 CONCLUSION

The 2020 land use and cover simulation achieved a 67% similarity with the actual landscape, effectively identifying land use and cover classes in more than half of the pixels. This success is attributed to the carefully selected model variables. After successful calibration and performance, the model was deemed viable for further scenario simulations, offering valuable predictive insights for future planning.

The projections indicate a significant increase in urban areas by 2050. They predict that urban area rates will increase from 32.1% in 2020 to nearly 43% by 2050, with most expansion occurring in agricultural lands, pastures, and forest fragments, leading to a decrease in landscape connectivity.

In the forecast, the municipality's boundaries expanded, reaching the surrounding areas in suburban. This differs from the compact city model, which aims to minimize the use of undeveloped land, such as a mosaic of agriculture and pasture and forest fragments. Preserving these lands in periurban areas is essential, as these areas provide critical ecosystem services, including flood mitigation, temperature regulation, and food production, which are vital for sustainable urban living.

Forest fragments are projected to decrease to 12% by 2050, with some converting to agriculture, pasture, and urban areas. The loss of forest fragments, especially in riparian zones, is a concern for urban biodiversity and landscape connectivity. Implementing innovative management practices in these areas can enhance air quality, microclimate, and overall urban biodiversity, contributing to the health and wellbeing of residents.

The decrease in landscape connectivity from 2020 to 2050 underscores the impact of urban expansion on forest fragmentation. Municipal governments must establish urban ecological networks to create more resilient cities. Continuous monitoring and analysis of green infrastructure and urban sprawl are crucial for sustainable urban development and achieving global urban environmental goals.

This study emphasizes the importance of urban sprawl simulations in addressing the challenges of urban sustainability and resilience, particularly in rapidly urbanizing regions like the Brazilian Atlantic Forest. Such simulations can aid cities in achieving Sustainable Development Goals, adhering to the New Urban Agenda recommendations, and participating in initiatives like the United Nations' Race to Resilience campaign. This is particularly pertinent for developing countries, where managing urban sprawl is critical for conserving green infrastructure and enhancing urban resilience.

While future urban expansion planning can provide a balanced approach to development and conservation, addressing uncertainties and limitations in assessing urban sprawl is essential. Future research should focus on enhancing modeling techniques, integrating economic and political variables, and formulating holistic urban planning strategies emphasizing sustainability and resilience.

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7 URBAN GROWTH SCENARIOS: EVALUATING COMPACT AND GREEN CITY STRATEGIES VERSUS BUSINESS-AS-USUAL USING LANDSCAPE METRICS

Abstract

Urban scenario simulation analyzes past and present urban patterns to forecast future outcomes, offering tools to evaluate decisions and guide planning strategies. This study uses a cellular automata model and landscape metrics to assess urban growth strategies in a Brazilian city within the Atlantic Forest Biome. Two scenarios were modeled for 2030 and 2050: a "business-as-usual" (BAU) scenario, reflecting current sprawl trends, and an "ecosystem services conservation" (ESC) scenario, focusing on green infrastructure and compact development. The ESC scenario, guided by the Priority Areas for Green Infrastructure (PAGI) model, integrates biodiversity and climate mitigation goals. Results showed that urban areas expanded significantly in the BAU scenario, from 32.11% of the landscape in 2020 to 43.03% in 2050, compared to slower growth in the ESC scenario, which reached 36.57% by 2050. The ESC scenario also exhibited greater aggregation, with fewer and larger patches and higher compaction, reflecting cohesive urban forms. Conversely, the BAU scenario achieved increased connectivity through fragmented, dispersed growth, resulting in higher environmental disruption. The ESC scenario emphasized compact development by expanding existing patches, minimizing habitat fragmentation, and enhancing connectivity sustainably. Comparing BAU and ESC scenarios highlights the benefits of compact urban forms in mitigating the adverse effects of urban sprawl, including habitat fragmentation, loss of ecosystem services, and increased spending on developing new urban infrastructure, such as utilities and streets. This study emphasizes the importance of planning constraints in urban scenario simulation to explore plausible futures with sustainable growth and ecological preservation.

Keywords: Urban planning, sustainable future, scenarios simulation, resilience planning.

7.1 INTRODUCTION

Cities are the world's leading drivers of growth and are at the center of discussion essential to ensuring a sustainable future (Acuto, Parnell and Seto, 2018). While cities offer economic opportunities and enhance the quality of human life, urbanization also brings challenges such as air and water pollution, traffic, overcrowding, loss of agricultural land,

habitat degradation, and a decline in biodiversity (Seto, Güneralp and Hutyra, 2012; UN, 2019). Land use changes, rapid urbanization, external pressures, and real estate speculation pose significant threats to sustainable and resilient urban futures (Shi *et al.*, 2022; Karimi and Sultana, 2024). In this context, cities are, in many ways, critical decision-making spaces where local actions have far-reaching global impacts (Keith *et al.*, 2022).

Developing nations, particularly in Latin America, face challenges in urban planning due to uncertainties related to future climate scenarios, as well as high rates of urbanization, continuous population growth, and a high risk of exposure to natural disasters (IPCC, 2014; United Nations, 2018). Climate change poses one of the most pressing challenges of the 21st century for urban areas (UN-Habitat, 2024). In this sense, understanding future urban sprawl patterns and impacts is critical for supporting resilience planning and decision-making in cities (UN-Habitat, 2022). Scenario simulation - exploring plausible futures through hypothetical alternatives - are essential in linking aspirational targets to concrete actions (Pandey, Prakash and Werners, 2021).

Urban scenario simulation examines past and current urban patterns and their connections to predict future outcomes (Amer, Daim and Jetter, 2013; Goodspeed, 2017). As narratives about the future, scenarios illustrate potential visions or alternatives, while serving as tools to evaluate the implications of decisions and policies (Chakraborty and Sherman, 2020; Zhou *et al.*, 2020). This approach is essential for testing multiple futures for cities or identifying relevant strategies and policies in the climate change context (Mallick, 2021).

Cellular automata models provide a robust framework for simulating urban dynamics, enabling the exploration of multiple future scenarios for cities (Chakraborty *et al.*, 2022). Scenario simulation models that utilize cellular automata algorithms are frequently used to simulate urban growth and land use changes (Ozturk, 2015; Wang, Murayama and Morimoto, 2021). The cellular automata model uses historical land use and land cover (LULC) data, as well as other essential information such as topography, roads, population statistics, and areas with growth restrictions, to calibrate and simulate changes in LULC (Saxena and Jat, 2019; Tripathy and Kumar, 2019). Flexible and minimally constrained by theoretical assumptions, cellular automata models are well-suited for spatial analysis using raster or grid representations and integrate seamlessly with raster data in Geographic Information Systems (GIS) (Maria de Almeida *et al.*, 2003).

Studies on urban development scenario simulations reveal a growing trend across Asia, North America, Europe, Africa, and South America (Wang, Murayama and Morimoto, 2021). These studies predominantly focus on developing countries, where rapid population growth and

significant urban expansion drive the need for comprehensive analysis and planning (Wang, Murayama and Morimoto, 2021). Assessing spatio-temporal LULC changes under different future scenarios can guide decision-makers, planners, and governments in understanding the impact of land-use planning decisions. This is particularly important for Brazilian cities within the Atlantic Forest, as this biome still has high biodiversity and supports more than 60% of Brazil's population (Myers *et al.*, 2000; Marques *et al.*, 2021; SOS Mata Atlântica, 2022).

Furthermore, urban sprawl projections, especially under green conservation scenarios, can guide cities in aligning with the 2030 Sustainable Development Goals (SDGs), particularly Goal 11 - make cities inclusive, safe, resilient and sustainable - while supporting the New Urban Agenda (UN-Habitat, 2020) and the 2050 Global Biodiversity Framework's Target 12, which emphasizes enhancing green infrastructure and urban planning to promote human well-being and biodiversity (CBD, 2023).

In this context, this research introduces a cellular automata model and landscape metrics approach to assess the impacts of different urban growth strategies on land use patterns and landscape connectivity in a Brazilian city within the Atlantic Forest Biome. Geospatial techniques and cellular automata algorithms were used to simulate two different urban sprawl scenarios for two years (2030 and 2050): the “business-as-usual” (BAU) scenario, which is based on the current urban sprawl trend, and the “ecosystem services conservation” (ESC) scenario, which simulates the implementation of green infrastructure and compact city development. The ESC scenario was defined using the Priority Areas for Green Infrastructure (PAGI) model (Chapter 5), which considers multiple ecosystem services—such as biodiversity, flood mitigation, heat mitigation, and social well-being—when determining priority areas for increasing green infrastructure in cities. The models were compared based on landscape metrics to understand the impacts on LULC patterns and landscape connectivity.

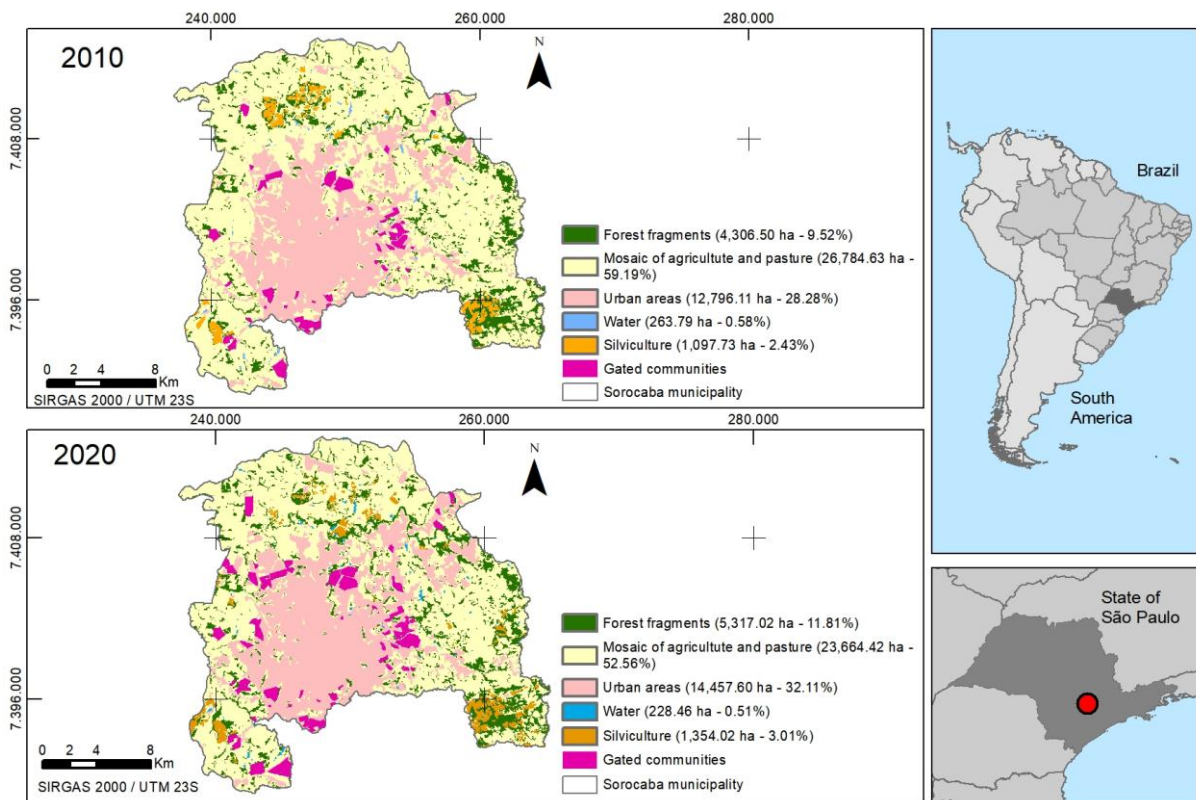
This approach allows us to simulate urban expansion patterns by exploring plausible futures, assessing the benefits and drawbacks of each scenario, and predicting the impacts of land use intensification on the city landscape. The results can support urban planning efforts, helping align them with local needs for resilience against climate change impacts and sustainable development.

7.2 MATERIAL AND METHODS

7.2.1 Study area

The study area is the Sorocaba municipality, a typical urban landscape in the Atlantic Forest context in southwest Brazil's São Paulo state (Figure 7.1). The municipality has 450 km² of a vast urban area surrounded by a highly fragmented seasonally dry tropical forest of small fragments with low connectivity (Ribeiro, Mello and Valente, 2022).

Figure 7.1. Sorocaba municipality, state of São Paulo, Brazil: location and land use and land cover in 2010 and 2020.



Source: Adapted from MapBiomias.

The climate is classified as Cwa by the Köppen system, i.e., subtropical, with a dry winter from June to September and a rainy summer from December to March. The mean annual temperature is 22°C, with January and February being the warmest months and January and December being the rainiest, with nearly 300 mm of monthly rainfall. The mean annual precipitation is 1,389 mm (CEPAGRI, 2020).

The local population grew from 586,625 in 2010 to 723,682 in 2022, an increase of 23.36% over 12 years. Sorocaba now has the ninth-largest population in São Paulo State, with 99% of its residents living in urban areas (IBGE, 2023). Consequently, urban areas in Sorocaba expanded significantly, growing from 12,796.11 hectares in 2010 to 14,457.60 hectares in 2020

(Figure 7.1). Remarkably, despite this urban growth, the area of forest fragments also increased, rising from approximately 4,300 hectares to 5,300 hectares during the same period (Figure 7.1).

In 2023, Sorocaba began updating its Master Plan, the principal framework for land use zoning that establishes rules, parameters, incentives, and instruments for urban development (Jornal Cruzeiro do Sul, 2023). This update is essential to ensure the adoption of modernized guidelines that promote sustainable, participative, and well-organized urban development.

During the public consultations, residents from various areas raised concerns about "urban disorder," citing challenges such as rapid population growth, the proliferation of high-rise buildings in traditionally low-rise residential neighborhoods, and insufficient infrastructure, such as streets and drainage systems (Jornal Cruzeiro do Sul, 2023). Specific issues included inadequate flood management, biodiversity loss, a lack of green spaces, and insufficient parks and squares to meet community needs (Jornal Cruzeiro do Sul, 2023). Despite these concerns, the Sorocaba council ignored the popular appeal and, with little discussion, approved a revision of the city's Master Plan at the end of December 2024 (Portal Porque, 2024b).

The haste of the process and the proposed changes sparked protests from citizens, who accused the draft of encouraging real estate speculation and favoring large construction companies (Portal Porque, 2024b). Several entities, councilors, and associations filed a lawsuit against the new Master Plan, citing a lack of transparency in the discussion process and insufficient time for meaningful public debate with Sorocaba's citizens (Portal Porque, 2024a). Given these controversies, this paper focuses on the 2014 Master Plan.

7.2.2 The model framework

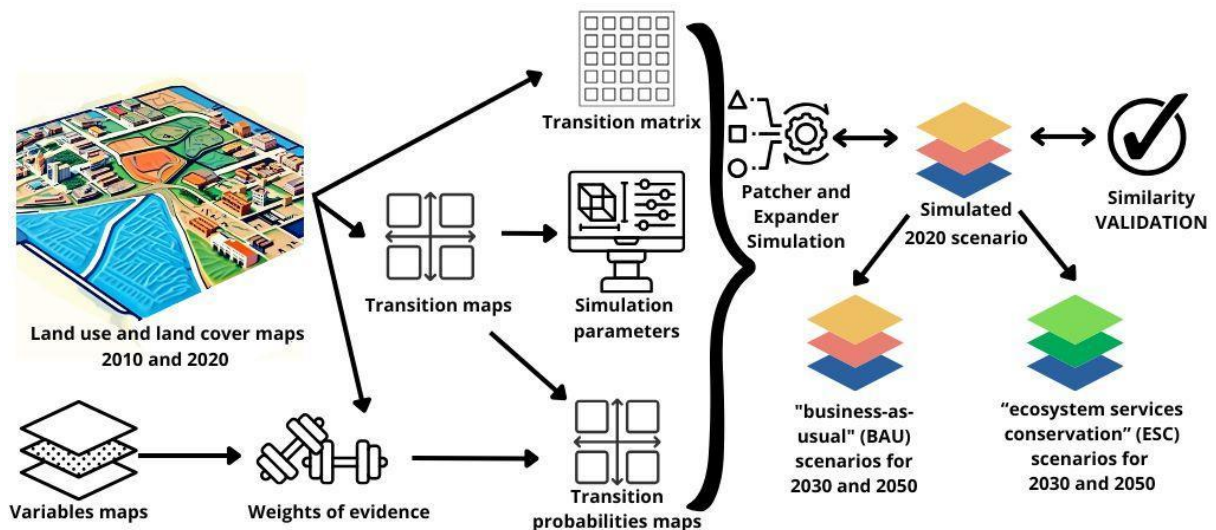
We used ten variables (addressing demography, distance to forest fragments, elevation, slope, land surface temperature, distance from rivers, distance from roads and streets, distance to Protected Areas, zoning map, and distance to parks and squares) and two historical LULC maps from 2010 and 2020 to calibrate, validate, and project the 2030 and 2050 urban land use forecasts through a cellular automata algorithms model (Figure 7.2).

Two urban prediction scenarios were tested and identified as:

- (a) "Business-as-usual" (BAU) scenario. This scenario represents the same growth pattern as previous ones, using Sorocaba's 2014 land use zoning and the 2010 - 2020 urban growth rate. It includes 20% of transitions by expansion, meaning the percentage of transitions occurring through the expansion of existent patches. The remaining 80% will be achieved through the expansion of new patches.

- (b) “Ecosystem Services Conservation” (ESC) scenario was developed using priority areas for green infrastructure identified by the Priority Areas for Green Infrastructure (PAGI) model (Chapter 5) and 2020 MapBiomas land cover data. This scenario emphasizes the significance of urban planning, environmental control, conservation and restoration of forest fragments, and compact city development. Priority areas for new green infrastructure were ranked on a scale from 0 to 10, with level 10 representing the highest priority for Sorocaba, as defined by the PAGI model (Figure 7.3A). The ESC map simulated reforestation over 1,221.84 hectares within these high-priority areas (Figure 7.3B) in Sorocaba, São Paulo, Brazil. Reforestation efforts targeted riparian zones and agricultural lands near urban centers (Figure 7.3B), converting specific MapBiomas 2020 land cover classes, including urban, pasture, and agricultural areas, into forest fragments to simulate restoration. Transitions were balanced, with 50% achieved by expanding existing patches and 50% by creating new patches. According to Qi *et al.* (2024), we considered this approach to support a compact city model, minimizing urban sprawl and aligning with the 50% transition matrix rate.

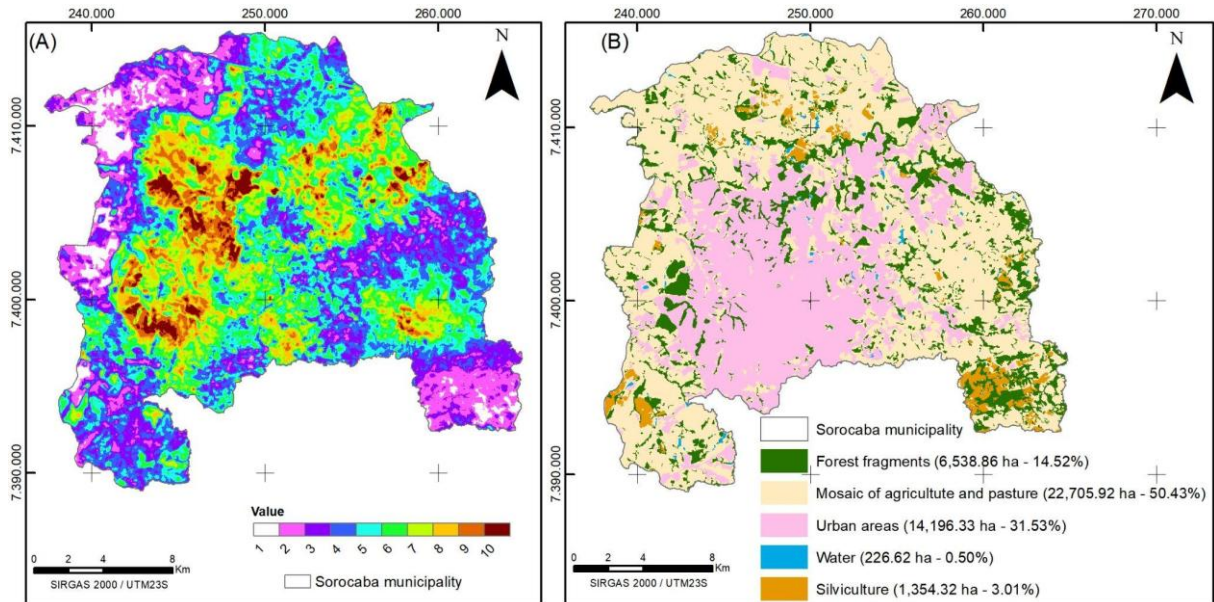
Figure 7.2. Steps used to develop the scenario simulation for 2030 and 2050 based on business-as-usual (BAU) and ecosystem services conservation (ESC).



Source adapted from Silva, Giannotti and Almeida (2020).

Figure 7.3. Priority areas for establishing new green infrastructure range from 0 to 10, with level ten (10) being the highest-priority for Sorocaba, as defined using the Priority Areas for

Green Infrastructure (PAGI) model - Chapter 5 (A). The “ecosystem services conservation” (ESC) map simulated reforestation over 1,221.84 hectares in the high-priority areas (B) in Sorocaba, state of São Paulo, Brazil.



Source: prepared by the author.

7.2.3 Spatial variables

The Sorocaba LULC data used for calibration encompassing 2010 and 2020 was obtained from the MapBiomias project (Souza *et al.*, 2020) - accessed directly from Google Earth Engine in raster format (30-m resolution, Collection 8.0) (Figure 7.1). Between 2010 and 2020, urban areas emerged as the dominant land cover class in the municipality (Ribeiro *et al.*, 2024).

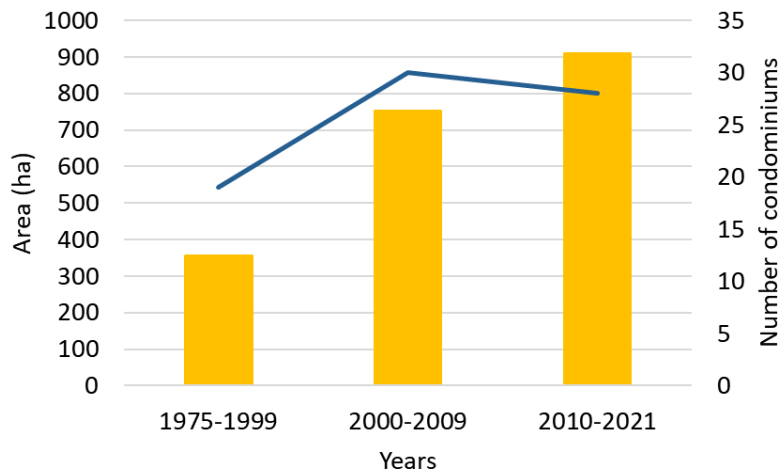
For this study, the land use and land cover (LULC) classes defined by MapBiomias were grouped into five categories: forest fragments, mosaics of agriculture and pasture, urban areas, water, and silviculture (Figure 7.1). The category labeled "mosaics of agriculture and pasture" encompasses areas of agricultural use where distinguishing between pasture and agriculture was not feasible (Souza *et al.*, 2020) and areas where both land uses were clearly present.

The municipality of Sorocaba features a dispersed and fragmented landscape, influenced by significant access corridors (roads that encircle the area) and urban patterns like gated communities and affordable housing developments far from the central city and established urban zones. As a result, new centralities have developed within the municipality.

The Sorocaba Municipality's Department of the Environment provided us with the boundaries of the gated communities within the city since 1975 (Figure 7.1 and 7.4).

The shapefile provides key information, including the year of approval for each condominium (Figure 7.4). Between 2010 and 2020, urban areas in Sorocaba expanded by 1,661.49 hectares (Figure 7.1), with gated communities contributing to over 54% of this growth (Figure 7.4). In contrast, the area occupied by slums increased only slightly, from 441 ha in 2010 to 792 ha in 2020 (Souza *et al.*, 2020).

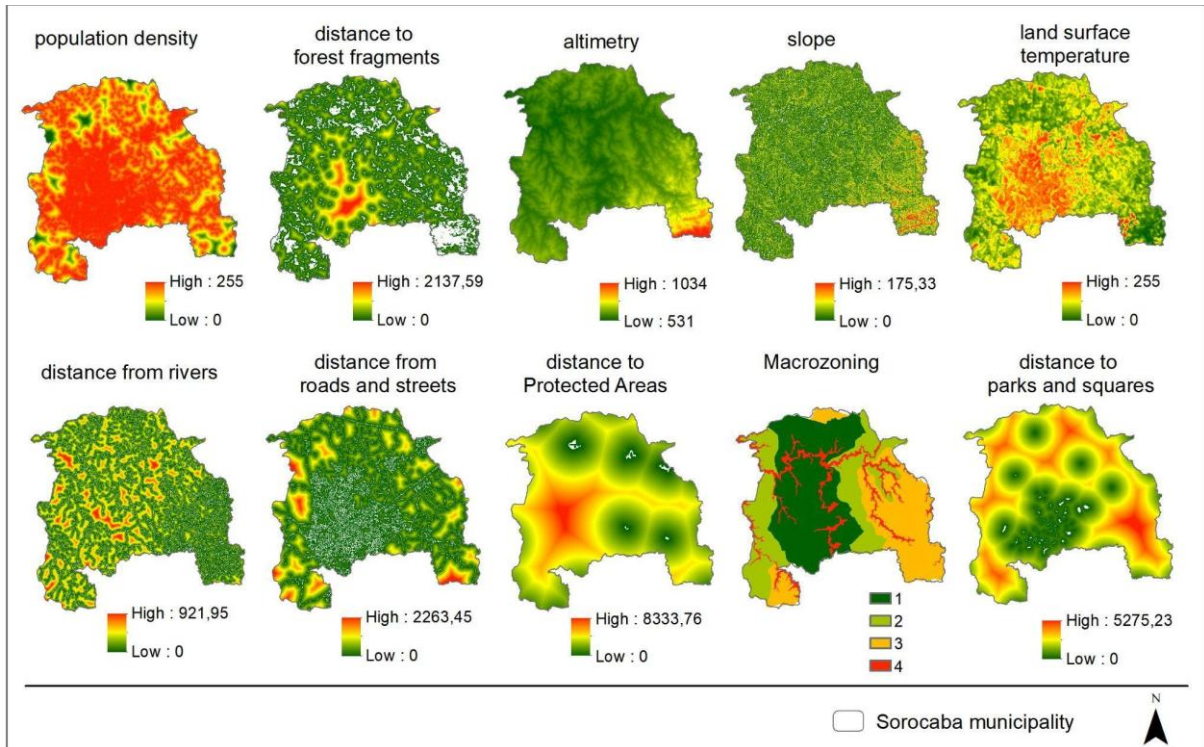
Figure 7.4. Gated communities’ expansions in number and area (ha) from 1975 to 2021 in Sorocaba, state of São Paulo, Brazil.



Source: prepared by the author.

We selected the following ten (10) variables as spatial determinants of urban sprawl (Figure 7.5).

Figure 7.5. Ten (10) variables used as spatial determinants of urban sprawl for Sorocaba, state of São Paulo, Brazil.



Source: prepared by the author.

- Population density: The dynamics of urban sprawl at various spatial scales are closely linked to population dynamics (Sapena and Ruiz, 2019). For population density, we used the "national address file for statistical purposes" from the Brazilian Institute of Geography and Statistics (IBGE, an acronym in Portuguese). This file contains the geographic coordinate data for all households in Brazil collected during the 2022 Census (<https://www.ibge.gov.br>). The composition was normalized to a standard scale by a linear fuzzy set membership function, ranging from 0 to 255.
- Distance to forest fragments: The presence of green spaces influences changes in land use in adjacent areas (Silva, Giannotti and Almeida, 2020). Green spaces can drive urban sprawl by attracting individuals seeking to live nearby, away from urban issues like poor air quality, noise, and limited open spaces (Jabbar, Nasar-u-Minallah and Yusoff, 2024; Koprowska, Łaszkiwicz and Kronenberg, 2020). In many Western countries, such as the U.S. and Latin American nations, cultural preferences for homes with private gardens close to nature contribute to peri-urban expansion (Bruegmann, 2008; Coy and Pöhler, 2002; Mejia and Montero, 2020). The distances from forest fragments established in 2020, based on MapBiomas data were calculated using the Euclidean method, ranging from 0 to 2,137.69 meters.

- Distance to roads and streets: indicating spatial and temporal autocorrelation, urban expansion predominantly follows existing transportation networks, occurring mainly along roads and streets (Garcia-López, 2019). Euclidean distances to roads and streets were calculated from the road and street network, ranging from 0 to 2,263.45m. The Department of the Environment of the Sorocaba Municipality provided vector data for roads and streets from 2014.
- Distance to rivers and water bodies: city development has always been closely related to water, leading to significant environmental degradation in riparian areas (Costa, 2007; Miguez *et al.*, 2015). Euclidean distances to rivers and lakes were calculated from drainage lines and water bodies, ranging from 0 to 921.95 m. The Department of the Environment of the Sorocaba Municipality provided the vector data for rivers and water bodies established in 2014.
- Distance to parks and squares and Protected Areas: The boundaries of Protected Areas, registered in the city between 2012 and 2016, were obtained from the Brazilian National Protected Areas Register (<https://www.gov.br/mma/pt-br>). Euclidean distances were calculated based on park and square limits and Protected Areas, ranging from 0 to 5,275.23m for parks and squares and 0 to 8,333.76m for Protected Areas. The Department of the Environment of the Sorocaba Municipality provided the vector data for parks and squares established in 2014.
- Macro zoning of Sorocaba's land use: Land use policies and urban development are closely linked (Macedo, 2008). The macro zoning of the Sorocaba land use was created based on the 2014 Master Plan and sourced from the Sorocaba Municipality's Department of the Environment. It is divided into four class levels for land use change policies: (1) minor restrictions, (2) moderate restrictions, (3) high restrictions, and (4) very-high restrictions (areas designated for conservation) (Sorocaba, 2014).
- The land surface temperature (LST): The LST exhibits spatial and temporal autocorrelation and is generally higher in urban areas due to heat retention by built materials (Ribeiro *et al.*, 2024). LST data were obtained from Ribeiro *et al.* (2024) procedures for the summer season - between December 2018 and March 2019. Landsat 8 OLI/TIRS data with minimal cloud cover were selected to compose a maximum-value temperature composition (the OLI sensor's Landsat crossing times are 12:00 p.m. and 1:00 p.m.). The composition was normalized to a standard scale by a linear fuzzy set membership function, ranging from 0 to 255 bytes.

- Physical variables: slope and elevation map. The 12.5 m resolution ALOS PALSAR digital elevation model (DEM) (acquisition date: 4 December 2018) was downloaded from the Alaska Satellite Facility Distributed Active Archive Center (<https://asf.alaska.edu/>) and used to generate the slope and elevation map. The slope map was calculated in percentages and DEM map in meters.

7.2.4 The model running process

We used DINAMICA EGO 7.0 (<https://csr.ufmg.br/dinamica/>), a landscape dynamics cellular automata model, to simulate the landscape for 2030 and 2050. The cellular automata local rule uses transition functions specifically designed to accurately replicate the dimensions and shapes of landscape changes (Soares-Filho, Coutinho Cerqueira and Lopes Pennachin, 2002).

Step 1 of the model processing included calculating the annual overall transition rate by cross-tabulating LULC maps. The transition rates set the net quantity of land use changes, which are indicated in percentages. For this study, we extracted data from MapBiomass (2010 and 2020) and analyzed the transition between forest fragments and urban areas and the mosaic of agriculture and pasture to urban areas.

The next step categorized continuous grayscale variables and calculated the Weights of Evidence (WoE) coefficients (Goodacre *et al.*, 1993). The WoE was calculated using a Bayesian probability-based approach that selects the spatial variables as the input and divides them into two subsets (Soares-Filho, Coutinho Cerqueira and Lopes Pennachin, 2002). One of the subsets is the static space variables, which for this study include five (5) variables: population density, elevation, slope, land surface temperature, and macro zoning land use map (Figure 7.5). Another subset is the dynamic variables, which are updated during model iteration, including for this study five (5) variables: distance to forest fragments, distance from rivers, distance from roads and streets, distance to Protected Areas, and distance to parks and squares. The WoE model is then used to generate the transition probability map.

The calibration of the model involved analyzing the variable's correlation to confirm the independence between each pair of spatial variables. Cramer coefficient and Joint Information Uncertainty were used (ranging from 0 to 1, where 0 indicates independence, and 1 signifies complete correlation). When the Cramer and Joint Information Uncertainty values are less than 0.5, there is no apparent correlation between the two variables (Bonham-Carter, 1994). This model's maximum correlation is 0.4730 in Cramer between elevation and land use zoning map.

In addition to the transition probability map, executing the model simulated through cellular automaton rules includes two complementary transformation functions: Expander and Patcher. The Expander function manages the expansion and contraction of existing patches, while the Patcher function controls the generation of new patches (Soares-Filho *et al.*, 2004; Soares-Filho, Coutinho Cerqueira and Lopes Pennachin, 2002). For this study, we used 20% for Expander in the BAU scenario and 50% in the ESC scenario, as described in Item 7.2.2.

The model validation in DINAMICA EGO uses exponential decay functions across multiple windows, varying from 1×1, 3×3, 5×5, 7×7, 9×9, and 11×11, with the fuzzy similarity measures applied within a neighborhood context. Spatial models require comparison within a neighborhood context because even maps that do not match exactly on a cell-by-cell basis may still exhibit similar spatial patterns and spatial agreement within a specific neighborhood context (Soares-Filho, Coutinho Cerqueira and Lopes Pennachin, 2002).

This study used 30 m for spatial resolution; hence, the validation was from 30×30 to 330×330 m, according to Soares-Filho, Coutinho Cerqueira and Lopes Pennachin (2002), who adapted the exponential decay functions (Hagen, 2003) to use in the multiple windows approach (Costanza, 1989). The results from the multiple windows approach show similarity values between the simulated and observed maps of difference for 2020. Values greater than 0.50 indicate high similarity scores, which may confirm the model's validation (Almeida *et al.*, 2008; Soares-Filho, Coutinho Cerqueira and Lopes Pennachin, 2002).

7.2.5 Evaluating Simulated Landscape Patterns

Landscape metrics are valuable in various planning phases, including analyzing landscape structure, supporting strategy selection and spatial design, evaluating planning scenarios, and providing indicators for landscape monitoring (Botequilha Leitão and Ahern, 2002). According to Botequilha Leitão and Ahern (2002), using multiple complementary metrics is essential for accurately capturing the spatial dimensions of complex landscape processes, as relying on a single metric is often insufficient.

We adapted the methodology from Aguilera, Valenzuela and Botequilha-Leitão (2011), which used specific spatial metrics to identify the urban spatial processes. We established relationships between the spatial characteristics of 2030 and 2050 and the urban spatial processes assessed (aggregation, compaction, and dispersion/isolation), distinguishing urban growth patterns (Table 7.1).

We employ eight (8) spatial metrics, selected at the landscape and class level, to specifically compare land use patterns in both scenarios (BAU and ESC). For this, we used landscape metrics: total class Area (CA), percentage of landscape (PLAND), number of patches (NP), mean patch size (MPS), mean Euclidean distance neighbor (ENN_MN), and mean shape index (SHAPE_MN) for assessing landscape patterns scenarios (McGarigal, 2015).

The Integral index of connectivity (IIC) (Pascual-Hortal and Saura, 2006) was used to evaluate urban land use dispersion/isolation. This index captures relevant changes in the landscape by integrating the amount of habitat and connectivity between them into a single measure (Pascual-Hortal and Saura, 2006). The IIC ranges from 0 to 1, increasing with improved connectivity (1 is the maximum connectivity) and is calculated as follows (Eq. 7.1):

$$IIC = \frac{\sum_{i=1}^n \sum_{j=1}^n \frac{a_i a_j}{1 + nl_{ij}}}{A_L^2} \quad (\text{Eq. 7.1})$$

where $a_i a_j$ is the area of patches (in this case, urban patches), nl_{ij} is the number of links in the shortest path (topological distance) between patches i and j .

The IIC index results were multiplied by 10,000 to facilitate the interpretation.

Table 7.1. Metrics for Assessing Urban Spatial Processes in Evaluating Planning Scenarios: Aggregation, Compaction, and Dispersion/Isolation.

Urban spatial processes	Metrics
Aggregation	Aggregation involves clustering patches to form larger ones, reducing the number of patches (NP), and increasing their mean size (MPS). Our estimation of the aggregation process was based on an analysis of the NP, MPS, and Percentage of Landscape (PLAND) values.
Compaction	Compaction creates rounded, compact patches, while elongation stretches the patches. The mean shape index (SHAPE_MN) measures this process, with lower values (nearly 1) indicating compaction and higher values indicating elongation.
Dispersion/Isolation	We used mean Euclidean distance neighbors (ENN_MN), Integral Index of Connectivity (IIC), and number of patches (NP) to assess the isolation of urban sprawl areas. A decrease in ENN_MN and an increase in NP and ICC reflect more considerable isolation and dispersion. This is an absolute fact because when new patches appear surrounding existing urban patches, the distance separating them decreases, and the connectivity among them increases.

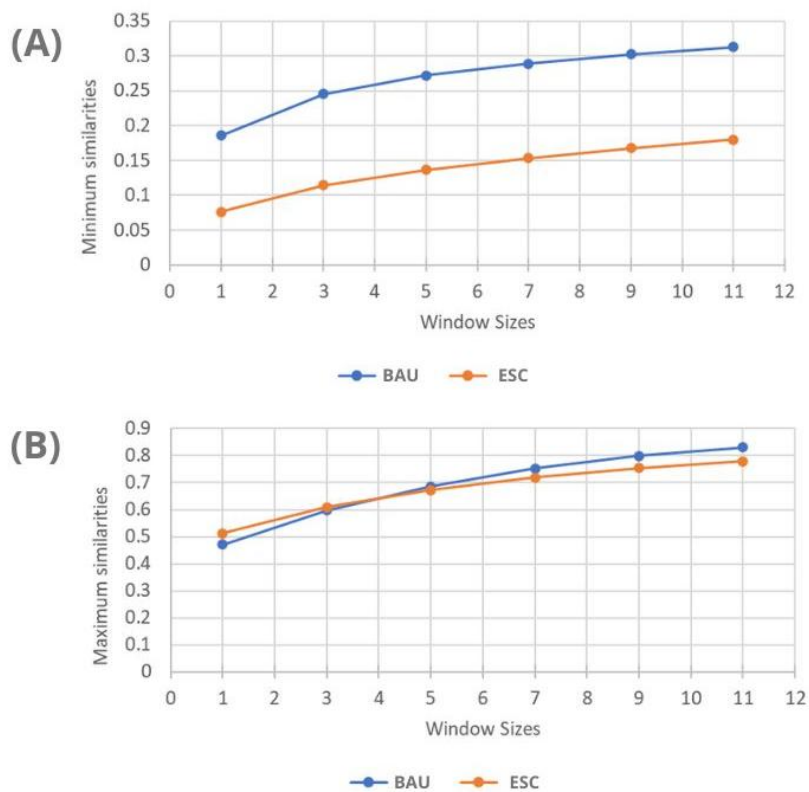
Furthermore, we used the IIC to evaluate how landscape patterns and land uses influence the connectivity of forest fragments in both scenarios (BAU and ESC). For this study, we adapted resistance values from Ribeiro, Mello and Valente (2022), as follows: forest fragments (1), mosaic of agriculture and pasture (60), urban areas (1000), water (70), and silviculture (65).

7.3 RESULTS

7.3.1 Model validation

The validation values of the models (BAU and ESC) were all within the satisfactory limit (Figure 7.6). The BAU scenario showed minimum similar spatial patterns above 25% at a spatial resolution of 150 m (5×5 window) (Figure 7.6A) and above 80% at 330 m (11×11 window) for maximum similarity (Figure 7.6B).

Figure 7.6. Minimum (A) and maximum (B) similarity as a function of multiple windows resolution for future land use and land cover model validation for Sorocaba, state of São Paulo, Brazil. This includes business-as-usual scenarios (BAU) and ecosystem service conservation (ESC) scenarios.



Source: prepared by the author.

In the ESC scenario, the minimum similarity (Figure 7.6A) was nearly 15% at a spatial resolution of 150 m (5×5 window) and achieved almost 80% at 330 m (11×11 window) in the maximum similarity (Figure 7.6B). The results obtained are generally considered satisfactory, according to Bonham-Carter (1994), demonstrating the model's ability to simulate urban development scenarios in the study area.

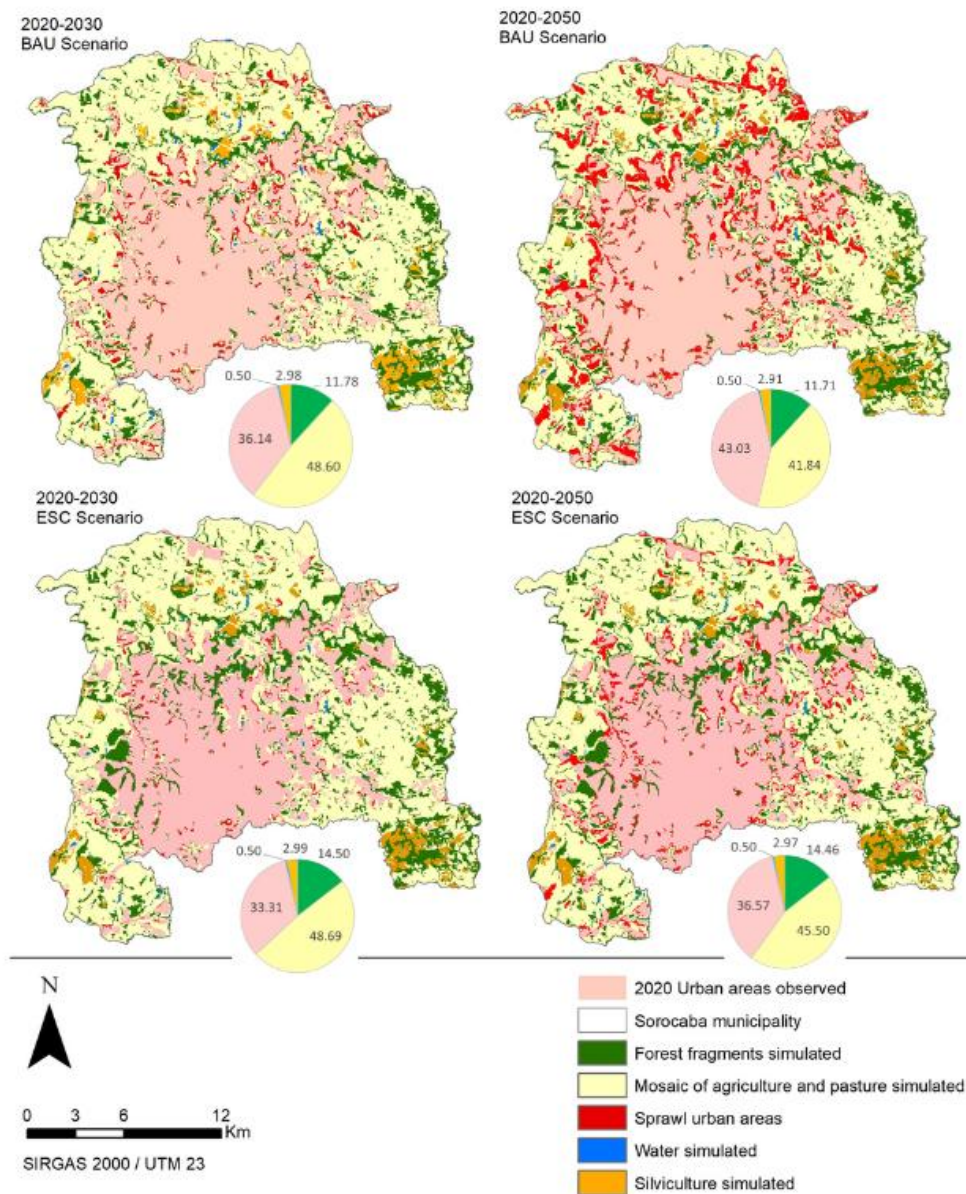
7.3.2 Evaluating simulated landscape patterns

Cellular automata model simulation generated four predicted urban sprawl scenarios (two BAU and two ESC scenarios) for 2030 and 2050 (Figure 7.7). Considering the base year (2020), the Sorocaba BAU scenario forecast showed that the urban area increased from 32.11% (14,457.60 ha) in 2020 to 36.14% (CA = 16,270.83 ha) in 2030 and 43.03% (CA = 19,372.50 ha) in 2050 (Figure 7.7).

In contrast, in the ESC scenario, the urban area represented 31.53% (CA = 14,196.33 ha) in 2020; it increased to 33.31% (CA = 14,998.77 ha) in 2030 and 36.57% (16,466.31 ha) in 2050 (Figure 7.7).

In the BAU scenario 2020, the observed forest fragments comprised 11.81% (CA = 5,317.02 ha) of the landscape. This percentage decreased slightly to 11.78% (CA = 5,304.78 ha) in 2030 and 11.71% (CA = 5,273.46 ha) in 2050 (see Figure 7.7). Similarly, the ESC scenario maintained approximately 15% of forest fragments between 2020 and 2050, which is almost 6,500 hectares.

Figure 7.7. Land use and land cover simulated for 2030 and 2050 for business-as-usual scenarios (BAU) and ecosystem service conservation (ESC) scenarios for Sorocaba municipality, São Paulo state, Brazil.



Source: prepared by the author.

The simulation indicates that urban sprawl primarily occurs in agricultural lands and pastures (Figure 7.7). In the BAU scenario for 2020, these areas (mosaic of agriculture and pasture) represent 52.56% (23,664.42 ha) of the total land; by 2030, the percentage is expected to decrease to 48.60% (CA = 21,878.10 ha), and by 2050, it is expected to further decrease to 41.84% (CA = 18,836.82 ha). This represents a reduction of 4,827.60 ha (20.40%) between 2020 and 2050 (Figure 7.7).

In the ESC scenario for 2020, the proportion of agriculture and pasture areas was close to 50% (CA = 22,705.92 ha), and this decreased nearly 49% (CA = 21,919.50 ha) in 2030 and 45.50% (CA = 20,486,37 ha) in 2050 (Figure 7.7).

In both scenarios, BAU and ESC, water, and silviculture each occupy nearly 0.50% and 3% of the landscape, respectively, in the observed 2020 year and projected years of 2030 and 2050.

In terms of aggregation, the BAU scenario showed a significantly greater increase in urban areas from 2020 to 2050 (CA = 14,457.60 ha in 2020; CA = 16,270.83 in 2030; CA = 19,372.50 in 2050) compared to the ESC scenario (CA = 14,196.33 ha in 2020; CA = 14,998.77 in 2030; CA = 16,466.31 in 2050), as well as a larger number of landscape patches (NP BAU for 2050 = 350 and NP ESC for 2050 = 296) (Table 7.2). When analyzing the mean size of urban areas (MPS), we observed that in the 2030 BAU scenario, the MPS decreased sharply compared to 2020, indicating a high fragmentation of the urban landscape (50.03 → 42.73) (Table 7.2). In contrast, the ESC scenario shows few new patches in the landscape, indicating that new urban areas expand from pre-existing patches, thereby increasing the urban mean area (MPS), which rises from 48.12 (2020) to 50.50 (2030), and 55.63(2050). In this sense, urban areas exhibited more intense aggregation in the ESC scenario than in the BAU scenario.

For compaction, in the BAU scenario, the SHAPE_MN decreased from 1.67 to 1.52 between 2020 and 2030, indicating a significant change in the landscape. After 2030, the metric slightly recovered by 2050 (1.52 → 1.60) but did not return to its original value. In the ESC scenario, the metric value decreases from 2020 to 2030 (1.66 → 1.58). However, from 2030 to 2050, there was a robust recovery (1.58 → 1.83), surpassing the 2020 value. Thus, the urban areas in the ESC scenario showed significant elongation compared with the BAU scenario in 2050.

When measuring the Dispersion/Isolation of new urban spaces, it is observed that in the BAU scenario, the increase in the number of urban patches (NP = 289 in 2020; NP = 385 in 2030; NP = 350 in 2050) in the landscape leads to a decrease in the average distances (ENN_MN = 71.17 in 2020; ENN_MN = 43.01 in 2030; ENN_MN = 32.63 in 2050) between them and an increase in connectivity (IIC = 2.9220 in 2020; IIC = 3.7311 in 2030; IIC = 5.2688 in 2050). On the other hand, dispersion in the ESC scenario occurs differently; there is no growth due to landscape dispersion, but rather due to the sprawl of the existing patch. As a result, the distance between patches decreases (ENN_MN = 72.69 in 2020; ENN_MN = 63.84 in 2030; ENN_MN = 31.90 in 2050), with the most noticeable decrease occurring in 2050, when there is a more significant increase in urban area. This leads to an increase in the integral index of connectivity (IIC = 2.9376 in 2020; IIC = 3.1976 in 2030; ICC = 3.7745 in 2050) and a decrease in the average distance (ENN_MN) (Table 7.2).

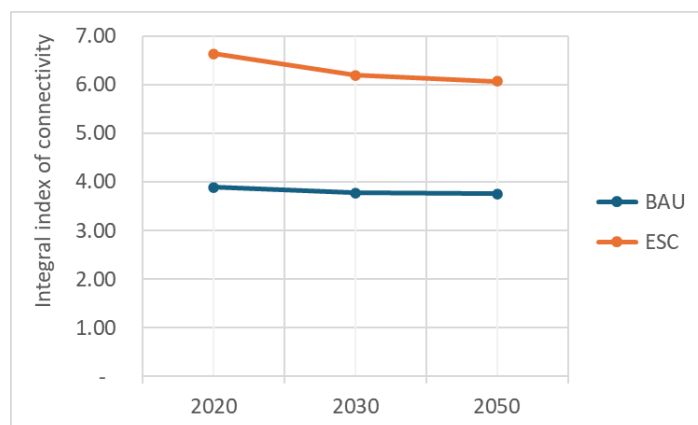
Table 7.2. Selected metrics to assess the urban growth pattern: mean euclidean distance neighbor (ENN_MN), number of patches (NP), mean patch size (MPS), mean shape index (SHAPE_MN), and Integral index of connectivity (IIC) for business-as-usual scenarios (BAU) and ecosystem service conservation (ESC) scenarios for Sorocaba municipality, São Paulo state, Brazil.

	ENN_MN BAU (m)	ENN_MN ESC (m)	NP BAU	NP ESC	MPS BAU (ha)	MPS ESC (ha)	SHAP E_MN BAU	SHAP E_MN ESC	IIC BAU (%)	IIC ESC (%)
2020	71.17	72.69	289.00	295.00	50.03	48.12	1.67	1.66	2.9220	2.9376
2030	43.01	63.84	385.00	297.00	42.73	50.50	1.52	1.58	3.7311	3.1976
2050	32.63	31.90	350.00	296.00	55.65	55.63	1.60	1.83	5.2688	3.7745

Forest fragments connectivity

In the ESC scenario, the Sorocaba forest fragments' Integral Connectivity Index (IIC) was higher than that of the BAU for all observed years (Figure 7.8). However, the expansion of urban areas has significantly impacted the landscape connectivity forecast under the ESC scenario more than the BAU scenario. In the ESC scenario, the connectivity index decreased from 6.64 in 2020 to 6.07 in 2050 despite a forecast of lower urban growth. In contrast, the BAU scenario decreased from 3.89 in 2020 to 3.76 in 2050.

Figure 7.8. Integral index of connectivity (IIC) for 2020, 2030 and 2050 for business-as-usual scenarios (BAU) and ecosystem service conservation (ESC) scenarios for Sorocaba municipality, São Paulo state, Brazil.



Source: prepared by the author.

7.4 DISCUSSION

The comparison of BAU and ESC scenarios demonstrates that integrating spatial planning constraints in land-use models is crucial in guiding sustainable urban development in Sorocaba. The magnitude of urban area increase is very different between the simulated scenarios. Simulations show that restricting urban growth (ESC scenario) maintains urban compactness and preserves almost 1,000 ha of land in 2030 and 2,600 ha in 2050 from the mosaic of agriculture and pasture compared to the BAU scenario (Figure 7.7). A sprawling urban layout often leads to inefficient land utilization, considerably increasing infrastructure expenses—up to six times greater than in more compact urban designs (CDRI, 2023). This inefficiency arises from the need for extended road networks, utilities, and services to accommodate dispersed populations, placing tremendous strain on municipal budgets and environmental resources (Vermeiren *et al.*, 2022).

The BAU scenario highlights an expansion pattern rooted in the municipality's historical trends (Figure 7.1). Urban sprawl has increased by nearly 65% since 1985 in Sorocaba, extending into peri-urban areas and transforming green and agricultural zones surrounding the urban center (Ribeiro *et al.*, 2024). Significantly, many of these emerging urban areas in Sorocaba consisted of gated communities, expanding from 357 hectares in 1999 to 2,000 hectares by 2021, primarily in peri-urban regions (Figures 7.1 and 7.4). In contrast, slum areas expanded more modestly, from 441 hectares in 2010 to 792 hectares in 2020 (Souza *et al.*, 2020). Gated communities, a growing trend in countries like the USA, Brazil, Mexico, South Africa, and parts of Europe (e.g., England, France, Spain, and Portugal), reflect urban residents' desire for improved security and well-being in environments increasingly perceived as precarious or unsafe, particularly in Latin American cities (Coy and Pöhler, 2002; Cruz and Pinho, 2009; Richmond and Kopper, 2022; Alkhafagie and Bassee, 2024). However, these developments are typically characterized by walls, fences, and restricted access, which reinforce spatial segregation and increase insecurity for neighboring communities (Silva and Lopes, 2022; Alkhafagie and Bassee, 2024). Additionally, they exacerbate challenges such as reduced urban mobility, diminished public life, fragmented urban areas, and privatization of public spaces (Silva and Lopes, 2022).

Conversely, the ESC scenario offers the potential to reverse this trend. Land consumption is significantly reduced in this model (Figure 7.7), as it envisions urban areas becoming denser and less sprawled, optimizing land use and minimizing the environmental

footprint of urban expansion. In this urban model, enhanced compactness helps preserve natural landscapes and ecosystem services, preserving carbon-sequestering areas like forests and grasslands (Lwasa *et al.*, 2022). This city model highlights an opportunity to direct future urban development towards low or net-zero greenhouse gas emissions while minimizing the loss of carbon stocks and sequestration capacity in agriculture, forestry, and other land uses resulting from the non-conversion of areas to urban uses (Lwasa *et al.*, 2022; UN-Habitat, 2024). In this regard, spatial planning for compact urban forms can integrate sustainable development goals while bringing climate mitigation strategies to urban systems (Facchini *et al.*, 2017; Lwasa, 2017; Stokes and Seto, 2019; Bibri, Krogstie and Kärholm, 2020). Furthermore, adopting a compact urban model can help preserve natural ecosystems, protect biodiversity, and enhance food security (UN-Habitat, 2024). By limiting urban sprawl, compact cities help decrease habitat fragmentation and preserve vital green spaces necessary for ecological balance and resilience (Nilon *et al.*, 2017). Additionally, compact urban forms integrate green and blue infrastructure, like parks and wetlands, into urban planning (Hansen *et al.*, 2019; Li *et al.*, 2016).

The results highlight significant differences in urban expansion between the BAU and ESC scenarios. Although both scenarios (BAU and ESC) showed an expansion of urban areas, land use patterns and policies significantly influence land use dynamics (Wang *et al.*, 2018). The contrasting growth patterns between BAU and ESC (Table 7.2) highlight the importance of enhancing the assessment of scenario simulations at the city scale. Identifying spatial patterns is increasingly recognized as a valuable approach to enriching conventional methodologies (Aguilera, Valenzuela and Botequilha-Leitão, 2011; Herzog and Lausch, 2001; Tan *et al.*, 2020). Grasping how landscapes work depends significantly on the connections between patterns and processes (Forman, 1995). These relationships are vital for modeling and predicting the ecological impacts of different planning alternatives (Forman, 1995).

The BAU scenario exhibited a 34% increase in urban area size from 2020 to 2050, with many fragmented patches (NP = 350 in 2050) and a decrease in compactness (SHAPE_MN: 1.67 → 1.52 → 1.60) (Table 7.2). This pattern reflects uncoordinated growth and increased fragmentation. In contrast, the ESC scenario shows slower, more structured growth (CA: 14,196.33 ha in 2020 to 16,466.31 ha in 2050) with fewer patches, larger, and more aggregated (NP = 296, MPS: 48.12 → 55.63). ESC compactness improves significantly (SHAPE_MN: 1.66 → 1.83), indicating cohesive urban forms and optimized land use (Table 7.2). Dispersion metrics further reveal that while both scenarios enhance connectivity by 2050, the BAU scenario achieves this through isolated and fragmented growth. In comparison, the ESC

scenario achieves connectivity improvements via the expansion of existing urban cores, resulting in reduced fragmentation and better planning outcomes (Table 7.2).

These results emphasize that urban planning policies focusing on inclusivity and environmental preservation, as achieved in the ESC scenario, strive to balance development with ecological and social objectives. Historically, new urban areas often emerge near existing ones, reflecting the spatial autocorrelation principle, where similar land uses tend to cluster together (Barredo *et al.*, 2003; Tobler, 1970). However, growth should not be dictated only by proximity but also by strategic urban planning that integrates multiple land-use objectives. This approach moves beyond speculative real-estate practices, focusing instead on creating cohesive urban fabrics that connect housing, infrastructure, and green spaces. Effective planning frameworks, such as transit-oriented development (TOD) and mixed-use zoning, promote compact and integrated urban forms that reduce sprawl and minimize environmental impact (Cervero and Kockelman, 1997; Ewing and Hamidi, 2015; Lu, Xiao and Ye, 2017). By prioritizing public needs over real-estate speculative, urban planning can foster equitable access to housing and public services, ensuring long-term sustainability and resilience in urban growth (Ratcliffe, Stubbs and Keeping, 2021).

To foster resilience in urban areas, prioritizing green infrastructure is essential (Staddon *et al.*, 2018). In Sorocaba, analyses of the connectivity of urban forest fragments using the Integral Index of Connectivity (IIC) reveal very low levels of connectivity, which are projected to decrease further by 2050 under current trends (Figure 7.8). The ESC scenario highlights that even a slight reduction in forest fragments can significantly affect overall landscape connectivity, given the limited availability of these forest fragments (Figure 7.8). Urban forest fragments, especially those located in areas designated for permanent preservation, parks, squares, and public roads, play a crucial role in maintaining ecological connectivity and biodiversity within urban environments (Ribeiro, Mello and Valente, 2022). These forest fragments serve as critical ecological corridors and stepping stones for wildlife movement, gene flow, and ecosystem services such as temperature regulation and air purification (Lynch, 2018; Teixeira and Martins, 2020).

The ESC scenario highlights the need to conserve and strategically manage forest fragments to prevent further loss of connectivity. Compact cities must value existing open spaces and create new ones to improve overall urban quality (De Martino, Franchino and Frettoloso, 2023). This could include improving green infrastructure by creating urban parks, tree-lined streets, and corridors that connect isolated areas, thus maintaining functional ecological networks within urban settings. These actions are crucial to mitigate the negative

effects of urban sprawl, protect biodiversity, and uphold ecosystem services vital for the health and well-being of urban residents (Sushinsky *et al.*, 2013).

Researchers, urban planners, and decision-makers worldwide increasingly recognize the importance of optimizing urban spatial expansion to address the negative consequences of urbanization (Zhou *et al.*, 2020). Unchecked urban sprawl often leads to habitat fragmentation, loss of ecosystem services, and increased socioeconomic inequalities, underscoring the need for a balanced and sustainable approach to urban growth (Brody, 2013; Li *et al.*, 2022).

In this regard, scenario simulations are essential for connecting aspirational objectives to executable strategies for decision-makers, planners, and governments, particularly for city managers and urban planners involved in the strategic design, planning, and management of resilient cities (Elmqvist *et al.*, 2018; Girardet, 2020; Pandey, Prakash and Werners, 2021). These tools enable stakeholders to evaluate alternative development pathways, predict their environmental, economic, and social impacts, and select strategies that align with long-term sustainability goals.

This study has certain limitations; it should be highlighted that integrating more specific methodologies could enhance this study. Techniques like spatial metrics along Concentric-Ring, Grid-Based Analysis, or a Diffusion-Coalescence Theory approach could enhance identifying changes in land occupation patterns and interpret local dynamics of urban growth (Menzori and Gonçalves, 2024; Wu *et al.*, 2021). Furthermore, finer spatial scales would facilitate the detection of small-scale dispersion processes, which could be overlooked with the current 30 m × 30 m cell size. Overall, these approaches would provide valuable support for the broader analysis presented in this study.

7.5 CONCLUSION

The comparison between the BAU and ESC scenarios highlights the importance of integrating spatial planning constraints into land use models to guide sustainable urban development in Sorocaba. The magnitude of urban area growth differs significantly between the simulated scenarios. The simulations indicate that restricting urban growth (ESC scenario) maintains urban compactness, preserving nearly 1,000 ha of land in 2030 and 2,600 ha in 2050 within the agriculture and pasture mosaic, compared to the BAU scenario. Dispersed urban growth often results in inefficient land use, significantly increasing infrastructure costs - up to six times higher than in more compact urban designs. This inefficiency arises from the need for

extended networks of roads, utilities, and services to serve dispersed populations, putting significant pressure on municipal budgets and environmental resources.

The BAU scenario reflects a pattern of expansion based on historical trends in the municipality. Since 1985, the urban area has grown by almost 65%, spreading into peri-urban areas and transforming green and agricultural zones around the urban core. Notably, a large part of these new urban areas in Sorocaba consists of gated communities, which expanded from 357 ha in 1999 to 2,000 ha in 2021, mainly in peri-urban areas. In contrast, slum areas have expanded more modestly, from 441 ha in 2010 to 792 ha in 2020. While gated communities represent a desire for greater security and quality of life, they often reinforce spatial segregation and increase insecurity in neighboring communities.

On the other hand, the ESC scenario has the potential to reverse these trends. This model significantly reduces land consumption, as it envisions denser and less dispersed urban areas, optimizing land use and minimizing the environmental footprint of urban expansion. A more compact urban model preserves natural landscapes and ecosystem services and contributes to climate mitigation strategies, such as reducing greenhouse gas emissions and maintaining carbon stocks in forested and agricultural areas.

The results of the landscape pattern analyses highlight significant differences in urban expansion between the BAU and ESC scenarios. The BAU scenario shows uncoordinated and fragmented growth, while the ESC scenario demonstrates more structured development with greater compaction and less fragmentation. These patterns highlight the importance of urban policies that balance development with ecological and social goals. Strategies such as transit-oriented development (TOD) and mixed-use zoning promote compact and integrated urban forms, reducing environmental impact and improving ecological connectivity.

The connectivity of Sorocaba's urban forests, analyzed by the Integral Connectivity Index (IIC), is projected to be very low, with a downward trend until 2050 in the BAU scenario. However, the ESC scenario highlights the importance of conserving and strategically managing forest fragments to prevent further losses in connectivity. Investing in green infrastructure, such as urban parks, tree-lined streets, and ecological corridors, is essential to mitigate the negative effects of urbanization and preserve ecosystem services vital to urban residents' well-being.

Finally, scenario simulations are essential for connecting aspirational goals to actionable strategies. They allow urban planners and managers to evaluate alternative development pathways and select strategies that align with long-term sustainability goals.

Although this study has limitations, such as the need for more specific methodologies and finer spatial scales, the analyses presented offer valuable support for planning resilient and sustainable cities.

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8 FINAL CONSIDERATIONS

This thesis aimed to determine whether green infrastructure planning in cities can provide multiple social and ecological benefits, particularly by delivering physical and emotional services that enhance human health, especially for socially vulnerable populations. The findings confirm that strategically planned green infrastructure significantly contributes to urban resilience, environmental sustainability, and social equity.

Using Sorocaba as a case study, this thesis developed a spatial model to identify priority areas for green infrastructure implementation. The model integrates key ecosystem services, including biodiversity, flood mitigation, temperature regulation, and social well-being. The findings reveal both synergies and trade-offs in green infrastructure planning. For example, flood mitigation and temperature regulation work well together to enhance urban resilience, while biodiversity conservation may conflict with temperature control. These trade-offs highlight the technical and political challenges of green infrastructure planning, emphasizing the need for a balanced, multifunctional approach to urban sustainability.

A well-connected green infrastructure network is essential for maximizing these benefits. By linking protected areas, parks, urban forest fragments, and blue-green infrastructure, cities can enhance ecological functions, support biodiversity, and strengthen climate adaptation strategies. Furthermore, equitable access to green spaces is crucial for addressing socio-spatial inequalities, ensuring that vulnerable communities benefit from ecosystem services promoting physical and mental health.

The literature review revealed that, despite being a relatively recent approach, green infrastructure is currently recognized for its capacity to combat climate change and enhance urban resilience. However, research on this topic remains concentrated in wealthier nations, while the Global South - particularly Latin America - faces significant climate challenges with limited academic exploration.

Through a comprehensive analysis of spatio-temporal changes in land use and land cover (LULC) and land surface temperature (LST) in Sorocaba from 1985 to 2020, this study highlighted the significant impact of urban expansion on temperature dynamics. Over the 36-year period, urban areas expanded by 64.75%, increasing more than 7°C in LST during the summer. In contrast, forested areas exhibited the lowest LST and a strong negative correlation with temperature (Spearman's rho between -0.382 and -0.75). These findings emphasized the vital role of green infrastructure in mitigating urban heat, underscoring the importance of implementing conservation policies to regulate LULC changes, protect peri-urban agricultural

lands, and integrate nature-based solutions into urban planning.

This study analyzed urban growth patterns using future scenario simulations to explore its role in urban planning further. A comparison between the "business-as-usual" (BAU) and "ecosystem services conservation" (ESC) scenarios demonstrated that compact urban designs can mitigate the negative effects of urban sprawl, such as habitat fragmentation, the loss of ecosystem services, and rising infrastructure costs. These findings reinforce the importance of integrating ecological conservation and planning constraints into urban development strategies to foster sustainable and inclusive growth.

Green infrastructure also directly impacts public health by mitigating climate effects, reducing urban heat islands, improving air and water quality, and providing recreational and social spaces that enhance emotional well-being and social cohesion. These benefits are particularly significant for vulnerable populations with limited access to healthy and safe natural environments.

Adopting the compact city model is also a key strategy for addressing climate challenges. This model promotes efficient land use, reduces unplanned urban sprawl, and facilitates access to urban services and public transportation, allowing for better integration of green infrastructure in densely populated areas. The resulting benefits - lower greenhouse gas emissions and improved resilience to extreme weather events - are significant for cities facing environmental and social disparities.

In conclusion, this study confirms that green infrastructure planning can provide multiple social and ecological benefits. By strategically integrating green spaces into urban environments, cities can enhance health, well-being, and resilience, particularly for socially vulnerable populations. The combined approach of green infrastructure networks, the compact city model, and equitable urban planning is essential for developing sustainable, inclusive, and adaptive cities that deliver long-term benefits to society and the environment.

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