UNIVERSIDADE FEDERAL DE JUIZ DE FORA

INSTITUTO DE CIÊNCIAS BIOLÓGICAS

PROGRAMA DE PÓS-GRADUAÇÃO EM BIODIVERSIDADE E CONSERVAÇÃO DA NATUREZA

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With great ecosystem services comes great responsibility: carbon sequestration and climate modelling in Brazilian urban forests

Juiz de Fora

2023

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Tese apresentada ao Programa de Pós-Graduação em Biodiversidade e Conservação da Natureza da Universidade Federal de Juiz de Fora como requisito parcial à obtenção do título de Doutor em Ciências. Área de concentração: Comportamento, Ecologia e Sistemática.

Orientador: Prof. Dr. Fabrício Alvim Carvalho

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Ficha catalográfica elaborada através do programa de geração
automática da Biblioteca Universitária da UFJF,
com os dados fornecidos pelo(a) autor(a)

Nunes Candido, Helder Marcos .
With great ecosystem services comes great responsibility: carbon sequestration and climate modelling in Brazilian urban forests / Helder Marcos Nunes Candido. -- 2023.
93 f. : il.

Orientador: Fabrício Alvim Carvalho
Tese (doutorado) - Universidade Federal de Juiz de Fora, Instituto de Ciências Biológicas. Programa de Pós-Graduação em Biodiversidade e Conservação da Natureza, 2023.

1. Áreas urbanas. 2. Bibliometria. 3. Mudanças climáticas. 4. Benefícios ecossistêmicos. 5. Modelagem climática. I. Alvim Carvalho, Fabrício, orient. II. Título.

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Aprovada em 26 de junho de 2023.

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Dedico este trabalho para minha mãe, Luciene.

AGRADECIMENTOS

Primeiramente, agradeço a Deus por todo o amparo e auxílio durante essa jornada do doutorado. Sem Ele, esse trabalho não seria feito.

Agradeço também minha querida mãe, Luciene Nunes, por todo apoio durante esses longos anos de trajetória acadêmica, por ter me apoiado e acreditado sempre em mim. Foram longos anos de luta, mas nós vencemos juntos. Te amo, mãe!

Agradeço ao meu pai, George, pelo auxílio durante meus anos de formação acadêmica.

Agradeço ao meu orientador, Professor Fabrício Alvim Carvalho, pelo apoio, incentivo e compreensão de sempre. Agradeço também por ter me apresentado e incentivado a aprender algumas das ferramentas que são utilizadas nessa Tese. Também agradeço o apoio e orientação nos momentos mais críticos.

Agradeço também ao meu querido amigo e parceiro em artigos, Professor Marcelo Leandro Bueno. Obrigado por estar sempre à disposição quando eu precisei de você. Aproveito para agradecer sua esposa, Professora Vanessa Pontara pela acolhida durante minha jornada em Mundo Novo.

Agradeço ao Professor Theodore A. Endreny por ter me recebido em Syracuse para um período de estudos. Obrigado por todos os feedbacks que auxiliaram a melhora desse trabalho. Aproveito para agradecer o apoio de Thomas Carter e Hui Chen durante o processo de ida e estadia para os Estados Unidos.

Um agradecimento especial vai para minhas amigas Emilly Pereira, Flávia Ferrari e Alice Rodrigues. Vocês foram essenciais durante meu doutorado, principalmente me ajudando quando as coisas ficavam difíceis. Obrigado também por aguentar meus memes durante os momentos mais inoportunos.

Não posso deixar de agradecer minha eterna Emilly, que partiu durante o doutorado, mas que me ajudou e me deu muito carinho durante toda a vida.

Um abraço especial a todos os colegas do Laboratório de Ecologia Vegetal da UFJF, principalmente Thales, Mari, Kelly, Valéria e Júlia.

Agradeço o carinho e os memes durante esses anos de doutorado enviados pelos amigos Mariah, Rosendinha, Natália e Uilson. Eles me alegraram bastante. Talvez.

Agradeço também o apoio e orações dos irmãos da Igreja Presbiteriana de Três Rios, que foram essenciais para meu crescimento espiritual durante do doutorado. Especialmente Reverendo Uriel Remy Rios e Lívia.

Agradeço a todos do Programa de Pós-Graduação por todo o apoio durante esses anos, especialmente os Professores Nathan Oliveira Barros e Roberto Júnio Pedroso Dias, que foram os coordenadores do PPG durante minha trajetória. Um agradecimento especial é direcionado para Priscila e Rosi. Agradeço também às Professoras Simone Jaqueline Cardoso, Juliane Floriano Lopes Santos, Rossana Correa Netto de Melo, Raquel Fernandes Mendonça e Larisse Faroni Perez.

Um agradecimento especial a todos os funcionários, alunos e amigos da Universidade Estadual de Mato Grosso do Sul, onde passei um breve período como Professor. Também agradeço aos irmãos da Primeira Igreja Batista de Mundo Novo, nomeadamente, Antônia e Tião, que me receberam de braços abertos.

Agradeço aos membros da banca, nomeadamente, Prof. Luiz Menini Neto, Prof. Nathan Oliveira Barros, Profa. Marcela de Castro Nunes Santos Terra e Profa. Vanessa Pontara, pelas contribuições para esse trabalho.

Agradeço à Coordenação de Aperfeiçoamento de Pessoal de Nível Superior e à Universidade Federal de Juiz de Fora pelas bolsas de pesquisa disponibilizadas durante esses anos. Também agradeço aos responsáveis pela correção dos valores das bolsas de doutorado, realizada em março de 2023.

"Porque o Senhor dá a sabedoria, e da sua boca vem a inteligência e o entendimento".

Provérbios 2:6

RESUMO

As florestas urbanas são ecossistemas únicos, frequentemente caracterizados por condições adversas e que enfrentam inúmeras pressões e ameaças. Elas contribuem para o bem-estar e a sustentabilidade das cidades, fornecendo uma ampla gama de serviços ecossistêmicos. Aqui, analisamos diferentes aspectos das florestas urbanas e seus serviços ecossistêmicos. No primeiro capítulo, observamos várias tendências na produção científica sobre os temas de serviços ecossistêmicos e florestas urbanas entre 1996 e 2022. No capítulo dois, analisamos os serviços ecossistêmicos prestados pelas áreas urbanas de 25 cidades da Floresta Atlântica no Brasil por meio do *software* i-Tree Canopy. Finalmente, no capítulo três, examinamos como as mudanças climáticas podem afetar as florestas urbanas brasileiras. Nossos resultados mostram que, entre 1996 e 2022, um total de 813 documentos foram publicados em 208 periódicos diferentes, com 20,62% de crescimento anual. Nossos resultados mostram que a produção científica na área tem crescido notavelmente ao longo dos anos. A produção científica apresentou uma tendência de crescimento consistente a partir de 2011. Isso sugere que a importância das florestas urbanas e dos serviços ecossistêmicos ganhou maior reconhecimento e atenção nos últimos anos. Nossos dados revelam que, juntas, as cidades estudadas sequestram um total significativo de 235,3 quilotoneladas de carbono e substanciais 864,82 quilotoneladas de CO_2 Equivalente (CO_2 Equiv.) anualmente. Além disso, juntas, elas também armazenam, por meio de sua vegetação, um total de 4.861,19 quilotoneladas de carbono e 17.824,32 quilotoneladas de CO_2 Equiv. Descobrimos que a estimativa monetária média do sequestro anual de carbono foi de US$ 3,57 milhões, enquanto a estimativa média armazenada foi de US$ 73,76 milhões. O correlograma de Pearson mostrou uma forte correlação positiva entre a densidade de moradores e a porcentagem de áreas impermeáveis em áreas urbanas ($p < 0,001$). Nossas descobertas mostram que as mudanças climáticas, mesmo em cenários mais otimistas, podem afetar severamente a adequabilidade ambiental das florestas urbanas em todos os domínios fitogeográficos, ou seja, o clima não será mais adequado para os tipos de florestas urbanas que estão agora presentes nas áreas estudadas. Isso é esperado especialmente na Floresta Atlântica e no Cerrado, dois *hotspots* de biodiversidade. Esses dois domínios fitogeográticos mais afetados abrigam a maior parte da população humana brasileira, uma das quais tende a sofrer impactos substanciais. Alertamos também que as florestas urbanas brasileiras podem ser drasticamente afetadas, tendo sua composição extremamente modificada e sua biodiversidade pode diminuir e até mesmo sofrer homogeneização. Portanto, são necessárias ações urgentes de mitigação e adaptação para o enfrentamento das mudanças climáticas e a manutenção dos serviços ecossistêmicos.

Palavras-chave: Áreas urbanas. Bibliometrix. Aquecimento global. Benefícios ecossistêmicos.

ABSTRACT

Urban forests are unique ecosystems that are frequently characterized by harsh conditions and face numerous pressures and threats. They contribute to the well-being and sustainability of cities by delivering a wide range of ecosystem services. Here, we analyze different aspects of urban forests an its ecosystem services. In chapter one, we observe several trends in the scientific production in the themes of ecosystem services and urban forests between 1996 and 2022. In chapter two, we analyze the ecosystem services provided by the urban areas of 25 cities of the Atlantic Forest in Brazil through the i-Tree Canopy software. Finally, in chapter three, we examine how climate change might affect Brazilian urban forests. Our results show that between 1996 and 2022, a total of 813 documents were published in 208 different journals, with 20.62% of annual growth. Our results show that scientific production in the area has grown notably over the years. Scientific production has shown a consistent growth trend from 2011 onwards. The results suggests that the importance of urban forests and ecosystem services has gained greater recognition and attention in recent years. Our data reveal that together, the cities studied sequester a significant total of 235.3 kilotonnes of carbon and substantial 864.82 kilotonnes of CO_2 Equivalent (CO_2 Equiv.) annually. Furthermore, together they also store, through their vegetation, a total of 4861.19 kilotonnes of carbon and 17824.32 kilotonnes of CO_2 Equiv. We found out that the average monetary estimate of annual carbon sequestration was $3.57 million, while the average stored estimate was $73.76 million. Pearson's correlogram showed a strong positive correlation between density of inhabitants and the percentage of impervious areas in urban areas ($p < 0.001$). Our findings show that climate change, even in more optimistic scenarios, may severely impact the environmental suitability of urban forests in all phytogeographic domains, that is, the climate will not be suitable anymore for the urban forest types that are now present in the areas studied. The impacts in the environmental suitability are expected especially in the Atlantic Forest and Cerrado, two biodiversity hotspots. The two most affected phytogeographic domains house most of the Brazilian human population, one of which tends to suffer substantial impacts. We also warn that Brazilian urban forests can be drastically affected, having their composition extremely modified and their biodiversity may diminish and even face homogenization. Therefore, urgent mitigation and adaptation actions are needed to tackle climate change and the maintenance of ecosystem services.

Keywords: Bibliometrix. Ecosystem benefits. Global warming. Urban areas.

RESUMO – DIVULGAÇÃO CIENTÍFICA

As florestas urbanas representam ecossistemas únicos, muitas vezes caracterizados por condições desafiadoras e confrontados com várias pressões e ameaças. Elas fazem diversas contribuições para o bem-estar e a sustentabilidade urbanos por meio da prestação de diversos serviços ecossistêmicos, benefícios diretos e indiretos que os ecossistemas naturais fornecem para as pessoas e a sociedade. Neste estudo, realizamos uma análise abrangente que engloba diferentes dimensões das florestas urbanas e seus serviços ecossistêmicos associados. No primeiro capítulo deste trabalho, investigamos a trajetória da produção científica no tema dos serviços ecossistêmicos e das florestas urbanas, abrangendo o período de 1996 a 2022. Nossa investigação identifica tendências e padrões perceptíveis dentro desse conjunto de literatura. Passando para o segundo capítulo, examinamos os serviços ecossistêmicos fornecidos pelas áreas urbanas em 25 cidades situadas na região da Floresta Atlântica do Brasil. Utilizando o *software* i-Tree Canopy, quantificamos e avaliamos esses serviços em detalhes. Por fim, no terceiro capítulo, iniciamos uma exploração das possíveis ramificações das mudanças climáticas nas florestas urbanas brasileiras por meio de modelagem computacional. Nossas descobertas mostram a vulnerabilidade desses ecossistemas urbanos às mudanças climáticas, mesmo em cenários mais otimistas. Essas transformações estão preparadas para modificar as condições ideais de sobrevivência das florestas urbanas em todos os biomas, especialmente na Floresta Atlântica e no Cerrado, que são altamente afetados abrigam a maioria da população humana do Brasil e, portanto, enfrentam impactos substanciais. Além disso, advertimos sobre as profundas transformações previstas nas florestas urbanas brasileiras, abrangendo alterações radicais em sua composição e uma possível redução da biodiversidade, possivelmente culminando em homogeneização florestal, ou seja, poucas espécies dominando uma área. Consequentemente, enfatizamos a necessidade de medidas rápidas e direcionadas de mitigação e adaptação para enfrentar os desafios impostos pelas mudanças climáticas e, ao mesmo tempo, garantir a continuidade dos serviços ecossistêmicos vitais derivados das florestas urbanas.

Sumário

1. General Introduction

Tropical forests play a key role in maintaining global biodiversity and providing ecosystem services. They hold great potential to function as carbon sinks, besides improving the quality of the water around them. Besides water quality improvement, forests can ameliorate urban air quality when removing pollutants and particulates and by sequestering and storing atmospheric carbon (Endreny, 2018). Pollution removal by vegetation can vary through some environmental characteristics, such as tree cover, pollution concentration, and the amount of precipitation, but it is known that tree presence in proper places can prevent human deaths and hospitalization due to respiratory and cardiovascular diseases, amongst others (Andreão et al., 2018; Mo et al., 2021; Nowak et al., 2018). Furthermore, the health benefits provided by the trees have socioeconomical impacts, since having a disease can decrease workers productivity, wellbeing, and income (Nowak et al., 2014). For instance, health issues caused by pollution, when avoided, can be estimated from USD 6 billion to USD 1 trillion (Andreão et al., 2018; Loughner et al., 2020).

Additionally, forests also have significant importance in the carbon sequestration and stocks, which have a substantial part in ecosystem processes in tropical forests and play a vital role in the global carbon cycle (Anderson-Teixeira et al., 2016; Lewis et al., 2015). Trees can act as a sink for CO_2 through carbon sequestration, fixing carbon to its physiological processes, such as photosynthesis, and stocking the excess of this as biomass (Nowak et al., 2013). Besides stocking and sequestrating carbon, trees can also benefit soil carbon input, even on abandoned areas (Jandl et al., 2007; Silver et al., 2000). Therefore, carbon sequestration is being taken into consideration in forest management strategies since global climate can be affected by deforestation, releasing carbon stored in the living plants and soils, and contributing to the increase of temperature, which can have a multilevel impact on ecosystems and socio-economic systems (Bala et al., 2007; Huang et al., 2020; Silver et al., 2000).

In this context, urban forests, which also play a vital role in the ecosystem, also provide several significant and highly valuable ecosystem services to society and biodiversity. However, urban forests have increasingly suffered from unplanned urbanization, which has diminished their space in the urban matrix over time. Climate Change is one of the main current challenges, and its effects can be catastrophic for the planet. Unsustainable anthropogenic expansive processes have accelerated and often have caused a series of negative impacts on the environment, i.e.: increased frequency of extreme weather events; changes in the distribution and abundance of wildlife, as climate is one of the most significant factors contributing to the distribution of species globally (IPCC, 2013; Nowak et al., 2013). Therefore, studies that bring together urban forests, ecosystem services and climate modelling are extremely important to meet the challenges that these areas will face in the future.

2. Chapter 1: Global trends in urban forests ecosystem services: a bibliometric analysis

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2.1 Abstract

Urban forests are unique ecosystems that are frequently characterized by harsh conditions and face numerous pressures and threats. They contribute to the well-being and sustainability of cities by delivering a wide range of ecosystem services. Studies on ecosystem services in urban forests began to be observed from 1996 onwards and have become increasingly present in scientific production. Bibliometrics and its interpretation can help to identify the impact of research, evaluate research quality, track productivity and identify trends and patterns. Here, we analyze, using the bibliometrix package, several trends in the scientific production in the themes of ecosystem services and urban forests. Our results show that between 1996 and 2022, a total of 813 documents were published in 208 different journals, with 20.62% of annual growth. From 2011 on, scientific production showed a constant growth trend until 2021, when it presented 143 publications, the highest value registered for one year. The authors of the analyzed articles belong to 54 different nations. The United States of America, China, and Italy presented most publications, respectively. The journal "Urban Forestry & Urban Greening" houses the largest number of articles published. Escobedo, F. J. and Nowak, D. J. were the authors with most published articles. The term "city" had the highest frequency of use in the abstracts, followed by "ecosystem" and "forest". Our findings show an increase in connections between the themes over time. Motor, basic, emerging or declining, and niche themes are presented. Our results show that scientific production in the area has grown significantly over the years. Scientific production has shown a consistent growth trend from 2011 onwards. The results suggests the importance of urban forests and that ecosystem services has gained greater recognition and attention in recent years. The findings contribute with valuable insights, providing a foundation for future research and decision-making.

Keywords: Bibliometrix. Biodiversity. Conservation. Urban ecosystems. Scientific productivity.

2.2 Introduction

The Anthropocene era is characterized by a multitude of significant global challenges, encompassing climate change, environmental degradation and injustice, and public health crises (da Rocha et al., 2018; Khojasteh et al., 2022). In this sense, urban forests are unique ecosystems that are frequently characterized by harsh conditions and face numerous pressures and threats, like limited growing space, adverse climatic conditions, loss of habitat, lack of management, and high levels of air pollution (Konijnendijk et al., 2006). Therefore, coping with urban and economic advances and at the same time conserving urban forests is characterized as a great current challenge that can have serious impacts in the future, since the majority of humanity tends to live in cities (United Nations, 2018). Failing to address this challenge effectively can have far-reaching consequences for the future.

Ecosystem services refer to the diverse benefits that nature, including urban forests, provides to humans and the environment. Urban forests contribute to the well-being and sustainability of cities by delivering a wide range of ecosystem services (Endreny, 2018; Nowak et al., 2020). Understanding ecosystem services is essential for policymakers, urban planners, scientists, and communities to make informed decisions regarding the conservation, management, and expansion of urban forests (Mitchell & Devisscher, 2022). As cities face mounting challenges posed by climate change, rapid urbanization, and declining biodiversity, understanding the significance of urban forests and their ecosystem services becomes increasingly important.

Consequently, it becomes necessary for more and more studies on the subject, which can help in several decision-making processes. Studies on ecosystem services in urban forests began to be observed from 1996 (Freedman et al., 1996) onwards and have become increasingly present in scientific production. A broad analysis of scientific production can offer insight into the evolution of a given subject in academia. In this context, bibliometric analysis is a scientific methodology that utilizes statistics and computer-assisted techniques to review and analyze all publications pertaining to a specific topic or field, which enables the identification of core research or authors and provides insights into their relationships and connections (Nicolaisen, 2010). Bibliometric analysis is a widely adopted and rigorous approach used to investigate and examine extensive collections of scientific data (Donthu et al., 2021). Therefore, bibliometrics and its interpretation can help to identify the impact of research, evaluate research quality, track productivity and identify trends and patterns that can be useful to broaden the existing horizons in science, as well as to identify potentials for the future.

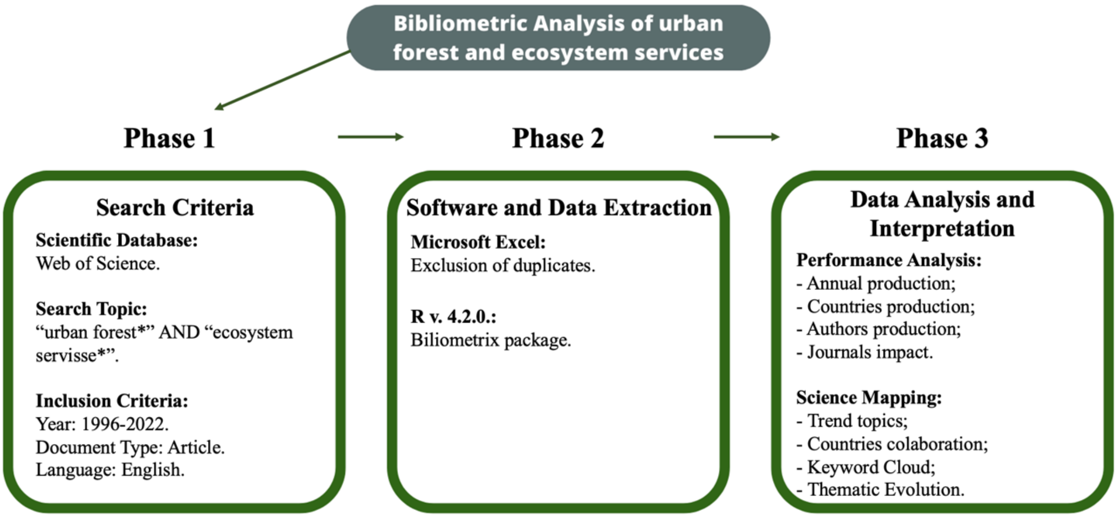
Here, we analyze, using the bibliometrix package (Aria & Cuccurullo, 2017) in R software (R Core Team, 2023), several trends in the scientific production in the themes of ecosystem services and urban forests, namely: annual scientific production; articles published by country; journals impact; authors with most publications; most cited papers; trend and hot topics; keyword cloud, and the thematic evolution. The indicators can provide a sense of the influence and importance of a particular piece of research or body of work. A comprehensive examination of the indicators can provide researchers, policymakers, and stakeholders with valuable insights into the impact and importance of research on ecosystem services and urban forests. By taking a holistic approach, this knowledge can guide informed decision-making, appropriate allocation of resources, and drive further research in these fields, ultimately addressing the most pressing and pertinent issues.

2.3 Material and Methods

Data acquisition

The ISI Web of Science (WoS) is known worldwide as a database that is a widely used resource for bibliometric analyses (Flores et al., 2022; Kemeç & Altınay, 2023; Torres et al., 2023). Web of Science database provides access to a large number of scientific journals (34,000 peer-reviewed scholarly journals from over 254 disciplines) across various fields and is known for its extensive coverage of citation data. Therefore, we used WoS as a database. We selected only papers written in English for data collection. The search query was: TS = ("urban forest*" AND "ecosystem service*"), where the asterisk used can be particularly helpful for locating variations in spellings. After excluding duplicates, we retrieved 813 papers that were published between 1996 and 2022 on 3rd April 2023 (Figure 1). The year 2023 was excluded from the research as it had not yet been concluded at the time of the study.

Figure 1 – Bibliometric analyses of urban forests and ecosystem services in the workflow



Source: Author’s own elaboration (2023).

Bibliometric Analysis

A bibliometric analysis is a quantitative method used to analyze academic literature, involving the use of bibliographies to describe, evaluate and monitor published research, which provides a general overview of a field (Garfield et al., 1964; Merigó & Yang, 2017). Scientific measurement mapping is a beneficial approach in dynamic fields of study because it provides a more profound understanding by examining different quantitative indicators through visualization (Li & Song, 2023).

The bibliometric analysis process is composed of five stages, as indicated by Zupic and Čater (2014): (1) research design, pointed out as the most crucial stage, being necessary to answer the main questions that one wishes to answer with the analyses; (2) compilation of bibliometric data, where the authors define the inclusion criteria of articles that will be analyzed; (3) analyses, in which bibliometric software is employed, in addition to performing exploratory statistical analyses; (4) visualization of the results, in which the best forms of presentation and grouping in graphs are selected and (5) interpretation, in which it is pointed out that bibliometric research does not replace an extensive process of reading in the field of study, which will favour the reaching of valid conclusions.

As bibliometrics is a constantly evolving discipline, software developers must update and integrate their tools to meet the changing needs of scholars which expands the software packages' scope of application (Xie et al., 2020). The purpose of this bibliometric review was to present a comprehensive view of the current knowledge status of the topic, offer a historical perspective of past research, and identify trends in the field. For this, all analyses were done using the bibliometrix (Aria & Cuccurullo, 2017) package in R (R Core Team, 2023), which offers the most comprehensive range of techniques and is appropriate for practitioners through the biblioshiny web interface (Moral-Muñoz et al., 2020). Therefore, the refined data retrieved from WoS was imported into bibliometrix for comprehensive analysis, involving information analysis, scientific mapping, and visual representation of the research subjects, such as authors, collaborations, journals, research trends and institutions. We identified the year, quantity, and authority of each paper. Furthermore, an analysis of the keywords in the index was conducted to gain a better understanding of the research trend regarding urban forests and ecosystem services.

To gain insights into the interplay between the main themes of research and their evolution over time, a Sankey diagram is presented in the results. The Sankey diagram visually represents the flow of parameters between two or more groups (Kennedy & Sankey, 1898). The visualization enables the examination of how different themes interact with one another within a longitudinal framework, thereby identifying the key pathways of thematic evolution and links between the themes (Wang et al., 2022). The Sankey diagram depicts theme clusters as individual nodes, with each node labeled according to the keyword that appears most frequently within that cluster (Otto et al., 2022). The size of each node is determined by the number of keywords associated with the corresponding theme, conveying the relative importance or breadth of the theme (Shi et al., 2020). The sets were defined to split the scientific production into three periods.

2.4 Results

2.4.1 Main information

The documents found encompass the scientific knowledge available about urban forests and ecosystem services (Table 1). Between 1996 and 2022, a total of 813 documents were published in 208 different journals, with 20.62% of annual growth and an average citation of 28.5 per paper. 95,21% of the papers showed more than one author, presenting an average of 4.58 (4) authors. 2,697 authors, from 54 countries and 974 different institutions produced the material analyzed. A total of 2,381 keywords were used by the authors.

Table 1 – Main information about papers concerning urban forests and ecosystem services between 1996 and 2022

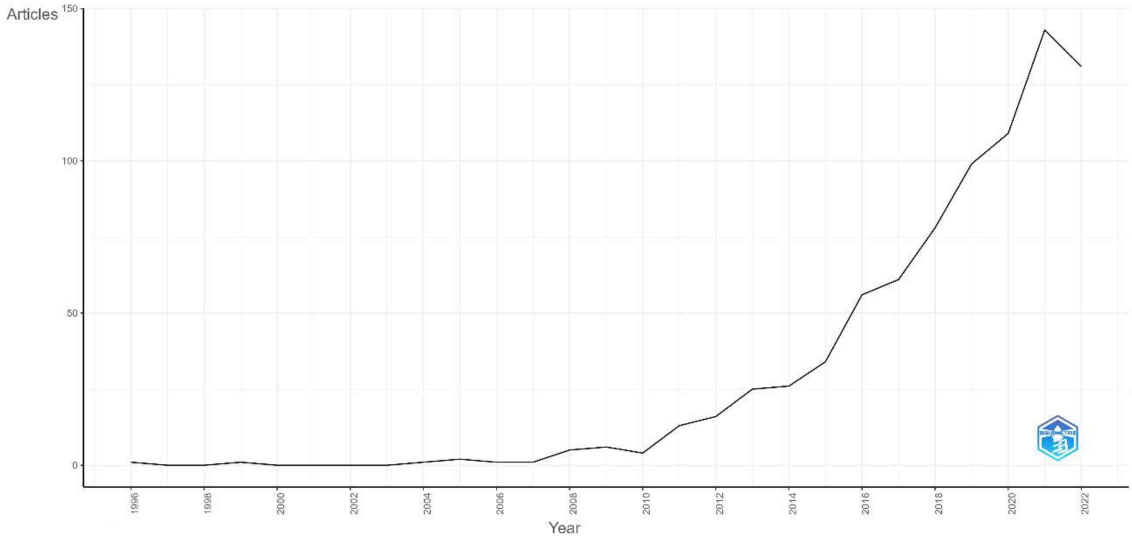
Main information about data	**Results**
Timespan	1996-2022
Sources	208
Documents	813
Annual Growth Rate %	20.62
Document Average Age	4.58
Average citations per paper	28.5
Author's Keywords	2381
Authors	2697
Single-authored docs	39
Co-Authors per Doc	4.53
International co-authorships %	29.77

Source: Author's own elaboration (2023).

2.4.2 Annual scientific production

Through the analysis of the number of papers published per year (Figure 2), our results showed that the theme was only partially explored in the past, since we can see few publications in 1996 (one publication) and at the beginning of the 2000s. Such tendency began to change from 2011 on, which presents 13 publications. From 2011 on, scientific production showed a constant growth trend until 2021, when it presented 143 publications, the highest value registered for one year. Subsequently, in the year 2022 occurred the first "drop" in production showing, however, 131 articles.

Figure 2 – Annual scientific production of papers concerning urban forest and ecosystem services



Source: Author's own elaboration (2023).

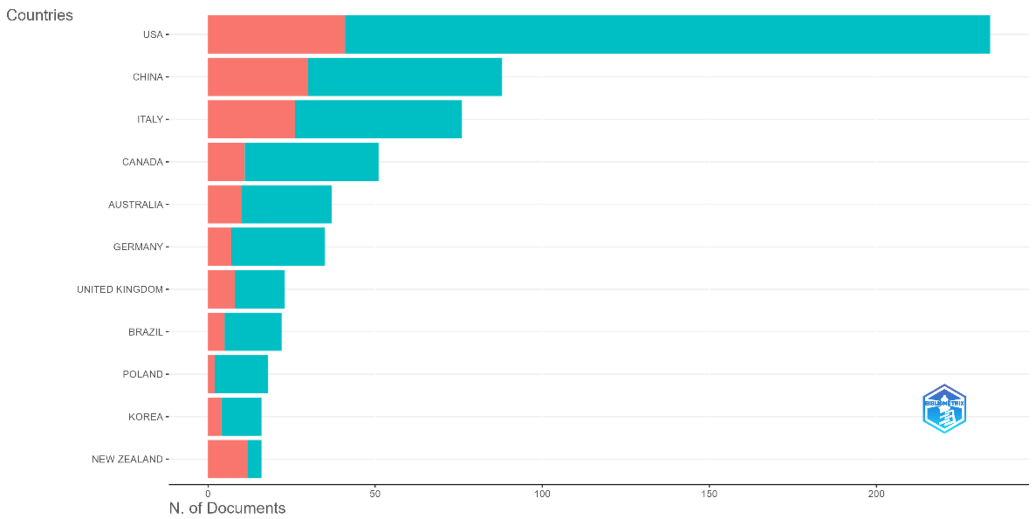
2.4.3 Articles published by country

As mentioned before, the authors of the analyzed articles belong to 54 different nations. Figure 3 presents a list of the most productive countries in the study field. The United States of America presented 234 articles (8,554 total citations), followed by China, with 88 publications (1,794 citations), and Italy, that has 76 papers with a total of 1,806 citations (Table 2).

All countries have more single country publications (SCP) than multiple country publications (MCP) (Figure 3). The countries that showed the most international collaboration in relation to total production were New Zealand (75% of published papers are MCP), China (34.09% MCP) and Italy (34.21% MCP).

Interestingly, even though Sweden is not on the list of countries with the highest scientific production in the area, it has the second highest number of citations (1,916), even though it has few articles and consequently the highest average number of citations per article. This result is due to the fact that the authors of the most cited article we found are Swedish.

Figure 3 – Most productive countries in the field of urban forests and ecosystem services. Blue bars represent Single Country Publications (SCP), and red bars represent Multiple Country Publications (MCP)



Source: Author's own elaboration (2023).

Table 2 – Number of papers, total citations and average citations per article of the most productive countries concerning urban forests and ecosystem services

Rank	Country	Papers	SCP	MCP	Total citations	Average Article Citations
1	USA	234	193	41	8554	36.6
2	China	88	58	30	1794	20.4
3	Italy	76	50	26	1806	23.8
4	Canada	51	40	11	1383	27.1
5	Australia	37	27	10	1354	36.6
6	Germany	35	28	7	906	25.9
7	United Kingdom	23	15	8	705	30.7
8	Brazil	22	17	5	132	6
9	Poland	18	16	2	82	4.6
10	Korea	16	12	4	182	11.4
10	New Zealand	16	4	12	449	28.1

Source: Author's own elaboration (2023).

2.4.4 Journals impact

According to our results, the papers concerning urban forests and ecosystem services were published in 208 different journals between 1996 and 2022. The journal "Urban Forestry & Urban Greening" (Impact Factor (IF)= 5.766) houses the largest number of articles (198), presenting a total of 4917 citations, with each article being cited 24.83 times on average (Table 3). It is followed by the journal "Forests" (IF= 3.282), which presented 65 papers, a total of 609 citations and an average of 9.36 citations each. In addition, “Landscape and Urban Planning” (IF= 8.119) presented 45 publications with 2011 citations, with each document presenting an average of 44.68 citations. The journal that presented the highest average citations (144.91), not taking into account the journals with only one publication, was “Environmental Pollution” (IF= 9.988), with only 12 publications, but 1739 citations.

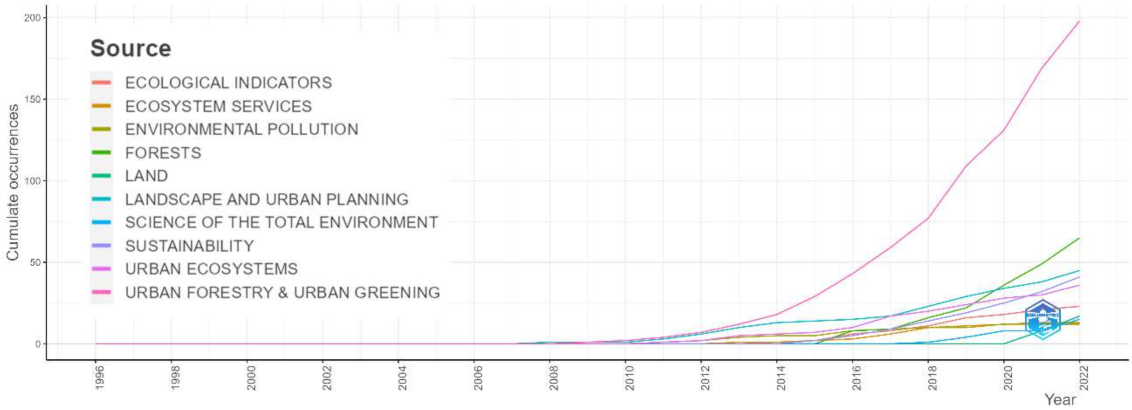
Table 3 – Journals with the highest number of publications in the field of urban forests and ecosystem services

Rank	Journal	Publications	Total Citations	Average citations/article
1	Urban Forestry & Urban Greening	198	4917	24.83
2	Forests	65	609	9.36
3	Landscape and Urban Planning	45	2011	44.68
4	Sustainability	41	407	9.92
5	Urban Ecosystems	36	851	23.63
6	Ecological Indicators	23	761	33.08
7	Land	17	56	3.29
8	Science of the Total Environment	15	250	16.66
9	Ecosystem Services	13	654	50.30
10	Environmental Pollution	12	1739	144.91

Source: Author’s own elaboration (2023).

As shown in figure 4, "Urban Forestry & Greening" has had, since 2010, a protagonism in publications related to the theme, appearing in 1st place when we analyze the total number of productions of the 10 journals that most published on urban forests and ecosystem services. The trend related to the journal has been maintained for 12 years, with a production considerably higher than the other journals. We can also note that "Forestry" only surpassed, concerning total publications, "Landscape and Urban Planning" in 2020.

Figure 4 – Production of the top 10 journals between 1996 and 2022 in the field of urban forests and ecosystem services

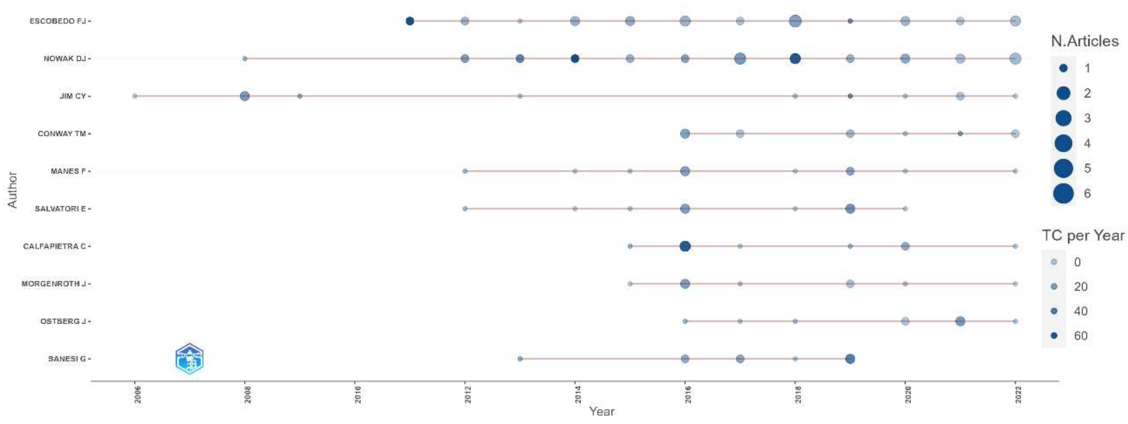


Source: Author’s own elaboration (2023).

2.4.5 Authors with most publications

Concerning the analysis at the author level, our results present the 10 authors who have published the most in the area (Table 4). In the first place, as the authors who have contributed the most to the advancement of knowledge in the area, we have a tie between Escobedo, F. J. and Nowak, D. J. Escobedo published 33 papers between 2011 and 2022, possessing a total of 1690 citations. Nowak D. J. also published 33 papers between 2008 and 2022 and has 2461 citations. In second place as the author with the most impact in the field, we have Jim C.Y., who has produced 12 papers from 2006 and has 892 citations. In third place, again, our data shows a tie between Conway T.M. with 11 papers (306 citations), Manes F. (412 citations) and Salvatori E. (444 citations). Figure 5 shows the production of the top 10 authors over the years and provides insight into the evolution of research in the field and the contributions of individual researchers.

Figure 5 – Production of the top 10 authors over the years. TC= Total citations



Source: Author's own elaboration (2023).

2.4.6 Most cited papers

The top 10 most cited papers can be found in Table 4. The total citations of these papers range from 250 to 1543. The three most cited papers are the ones written by Bolund and Hunhammar (1543 citations) (1999), Escobedo et al. (583) (2011), and Nowak et al. (437) (2014).

Table 4 – The top research in urban forests and ecosystem services topic

Rank	Authors	Title	DOI	Year	TC	TC/Year	Journal
1	Bolund & Hunhsmmar	Ecosystem services in urban areas	10.1016/S0921-8009(99)00013-0	1999	1543	61.72	Ecological Economics
2	Escobedo et al.	Urban forests and pollution mitigation: Analyzing ecosystem services and disservices	10.1016/j.envpol.2011.01.010	2011	583	44.85	Environmental Pollution
3	Nowak et al.	Tree and forest effects on air quality and human health in the United States	10.1016/j.envpol.2014.05.028	2014	437	43.70	Environmental Pollution
4	Livesley et al.	The Urban Forest and Ecosystem Services: Impacts on Urban Water, Heat, and Pollution Cycles at the Tree, Street, and City Scale	10.2134/jeq2015.11.0567	2016	355	44.38	Journal of Environmental Quality
5	Nowak et al.	Carbon storage and sequestration by trees in urban and community areas of the United States	10.1016/j.envpol.2013.03.019	2013	344	31.27	Environmental Pollution
6	Venter et al.	Urban nature in a time of crisis: recreational use of green space increases during the COVID-19 outbreak in Oslo, Norway	10.1088/1748-9326/abb396	2020	324	81	Environmental Research Letters

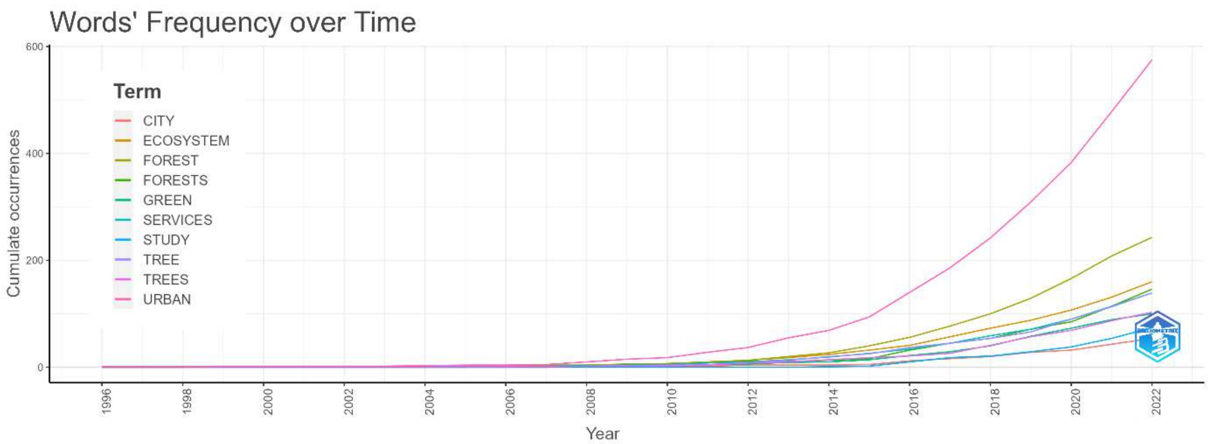
7	Davies et al.	Mapping an urban ecosystem service: quantifying above-ground carbon storage at a city-wide scale	10.1111/j.1365-2664.2011.02021.x	2011	289	22.23	Journal of Applied Ecology
8	Mckinley et al.	A synthesis of current knowledge on forests and carbon storage in the United States	10.1890/10-0697.1	2011	267	20.54	Ecological Applications
9	Jim & Chen	Assessing the ecosystem service of air pollutant removal by urban trees in Guangzhou (China)	10.1016/j.jenvman.2007.03.035	2008	261	19.23	Journal of Environmental Management
10	Dobbs et al.	A framework for developing urban forest ecosystem services and goods indicators	10.1016/j.landurbplan.2010.11.004	2011	250	30	Landscape and Urban Planning

Source: Author's own elaboration (2023).

2.4.7 Hot topics

Since 2014, the most covered topics in research regarding the studied topic have remained almost the same, with minor exceptions. The term "city" stands out as the one with the highest frequency of use in the abstracts of the analyzed articles, having, in 2022, almost 600 mentions in accumulated frequency. Then, with just over 200 mentions, the term "ecosystem" comes in second place. Next, we observe the terms "forest" and "forests" in 3rd and 4th place, respectively. The term "green" appears soon after, in 5th place. The remaining terms can be seen in Figure 6.

Figure 6 – Words Frequency over time in the research topics



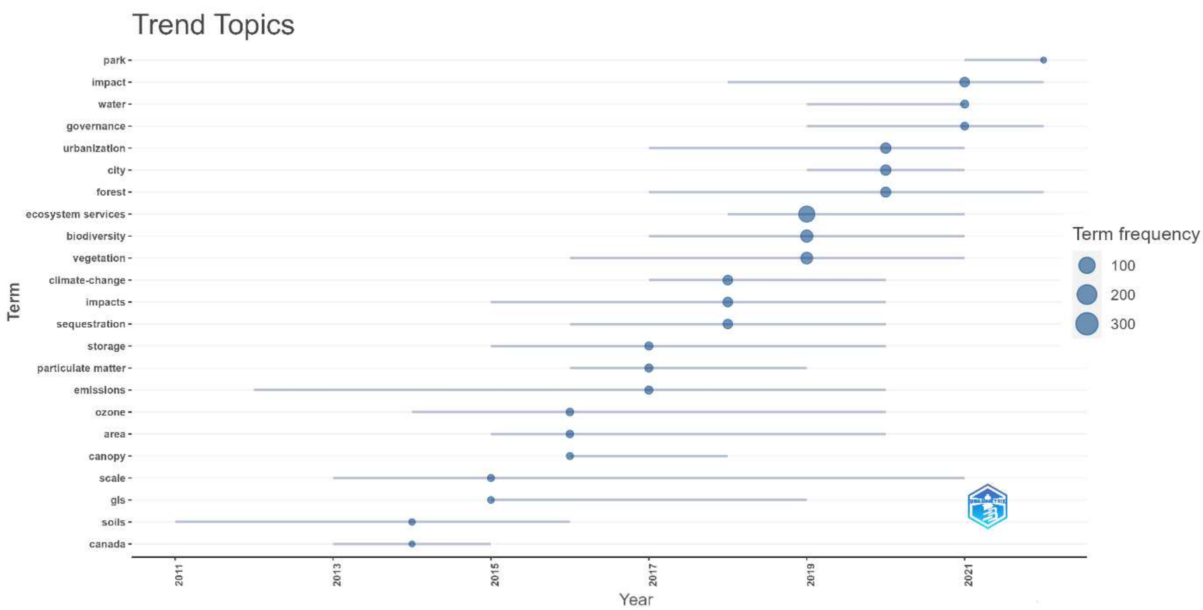
Source: Author's own elaboration (2023).

2.4.8 Trend Topics

Analyzing the trend topics used in the abstracts of the analyzed articles from 2011 to 2022, it is possible to see a change in the most commonly used terms through the years. In 2011, we had a prevalence of the use of the words "soils" and "emissions". Later, in 2015, the terms continued to be widely used, but other terms are also added, such as "GIS", "scale", "storage", and "impacts". In 2017, a greater use of the terms "particulate matter", "sequestration", "climate change", "biodiversity", "forests", and "urbanization" appeared.

The term "ecosystem services" began to be used more frequently in 2018, reaching the highest usage in articles published in 2019. The terms "biodiversity" and "vegetation" also reached the highest usage in 2019. It is also in 2019 that the terms "governance", "water", and "city" begin to be most viewed in article abstracts, with "governance" and "water" reaching their highest frequency in 2021. Since 2021, we have as the most used terms in abstracts the following words: "park", "impact", "governance" and "forest".

Figure 7 – Trend topics over time in the field of urban forests and ecosystem services



Source: Author's own elaboration (2023).

2.4.9 Keyword cloud

Figure 8 displays a word cloud with the 50 keywords that have been most commonly used in the field of "ecosystem services" and "urban forest" research from 1996 to 2022. The size of the keywords in the figure represents their importance and frequency of use within the field. It can be seen that the words "ecosystem services", "urban forest", and "urban forestry" are the most common, followed by "green infrastructure".

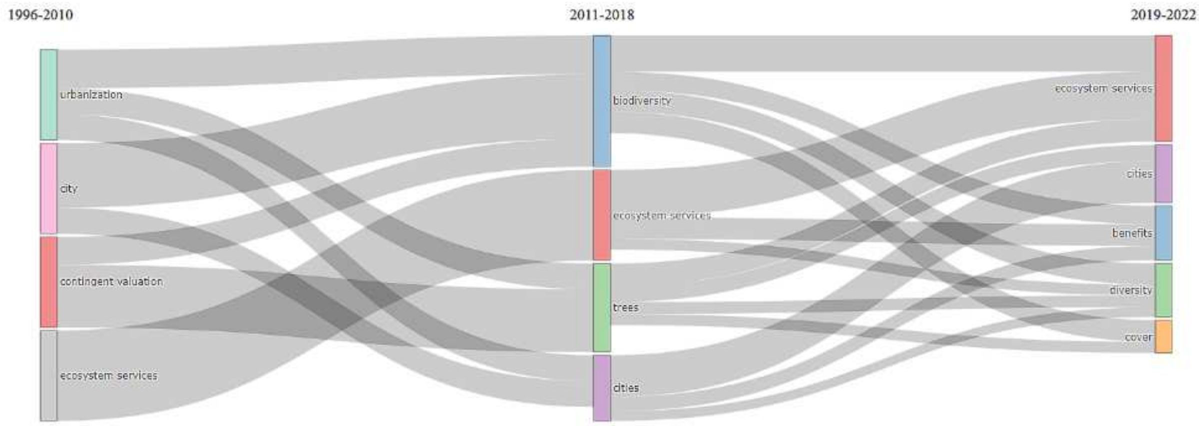
Figure 8 – Word cloud presenting the top 50 words most used in the keywords of papers in the field of urban forests and ecosystem services

Source: Author's own elaboration (2023).

2.4.10 Thematic Evolution

Our results (Figure 9) show an increase in connections between the themes over time. Each block on the map represents a theme identified by the most frequently used keyword. During the process of thematic evolution, a significant number of connections and intense conversion relationships are observed. It can be seen that the words "ecosystem services" were always present in the three periods analyzed, and they connect to "benefits" and "diversity" as of 2019. In the second period, it is possible to observe the prevalence of the theme "biodiversity", which is later linked to the themes "diversity", "benefits", and "cover" in the third period. The "city/cities" themes also appear as the most used keywords in all three periods, the theme city/cities also appear as the most used keyword in all three periods, always connected with either "biodiversity" or "diversity. The themes "benefits" and "cover", both addressed in this study, appear as emerging themes since 2019.

Figure 9 – Thematic evolution in ecosystems services and urban forests in three different periods



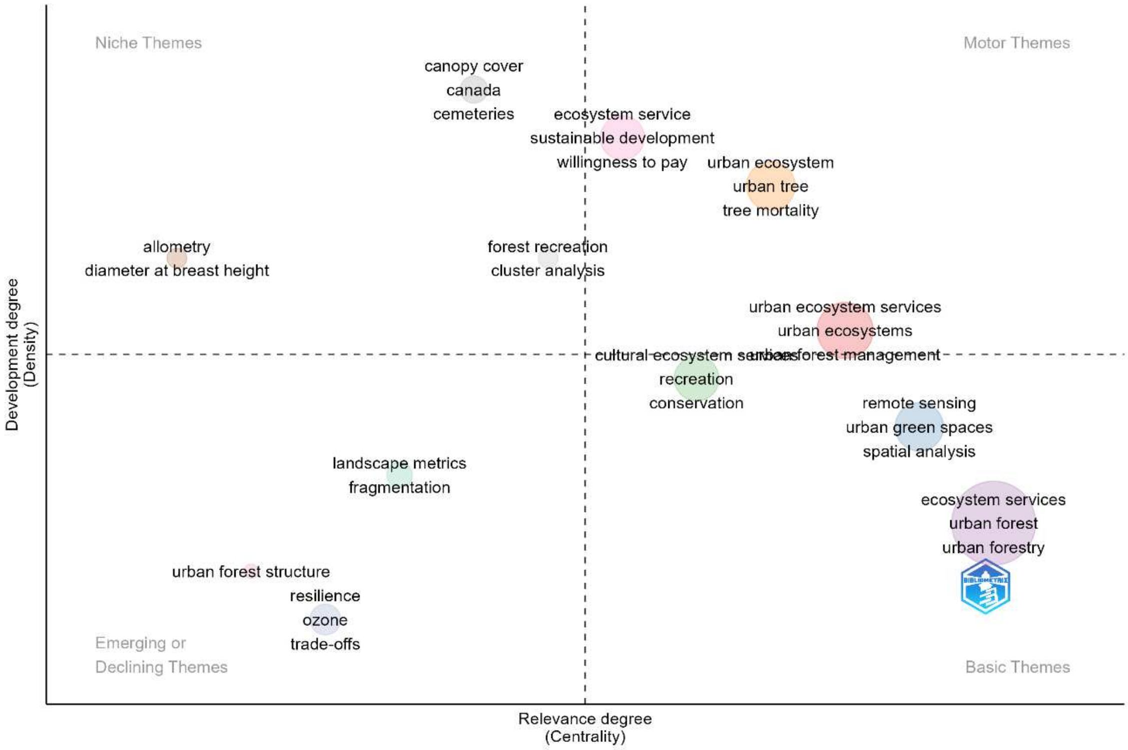
Source: Author's own elaboration (2023).

2.4.11 Strategic diagram

The relative location of each cluster in the quadrant, which reflects the intellectual progress within the research theme, is determined by the values of centrality (axis x) and density (axis y) (Kim et al., 2021). Kim et al. (2021) also defined the four quadrants found in the strategic diagram: themes from quadrant 1 (motor themes) are well developed and have reached research maturity; quadrant 2 (basic themes) are defined as ideas that have become very popular but did not reach research maturity yet; quadrant 3 (emerging or declining themes) presents research that is not active yet, and, therefore, research maturity is not yet high; quadrant 4 (niche themes) presents developed but isolated themes that have low accessibility to general researchers.

Our results present as the main motor themes the following keywords: "urban ecosystem", "urban tree", and "tree mortality". The main basic themes presented are: "ecosystem services", "urban forest", and "urban forestry". The main emerging or declining themes are: "resilience", "ozone", and "trade-offs". The main niche themes are: "canopy cover", "Canada", and "cemeteries". More themes can be found in Figure 10.

Figure 10 – Strategic diagram showing niche, motor, emerging or declining and basic themes of urban forests and ecosystem services scientific production.



Source: Author's own elaboration (2023).

2.5 Discussion

In this study we conducted a bibliometric analysis to examine the characteristics of publications concerning urban forests and ecosystem services. The results of our analysis provide important insights into the academic production on ecosystem services in urban areas since 1996. Studying ecosystem services in urban areas is of paramount importance and can empower us to proactively address the challenges posed by climate change and promote the long-term well-being and sustainability of urban environments. In this sense, bibliometric analysis provides valuable insights into the scientific landscape, research impact, collaboration opportunities, and research gaps that can be valuable to future research and to decision-making (Debackere et al., 2004).

Our results show that scientific production in the area has grown significantly over the years, an extremely important fact, since the ecosystem services provided by green infrastructure have strong benefits for human health (Bowen & Lynch, 2017). It is interesting to note the relatively low number of publications in the early years of the study period, with only one publication in 1996 and a few publications in the early 2000s. The results suggests that the topic was not as widely explored or recognized in the scientific community during that period. However, it is encouraging to see that scientific production on this topic has shown a consistent growth trend from 2011 onwards, with a notable increase in the number of publications in 2021, reaching its highest value. Franzen (2003) says that environmental concern is a global phenomenon, which shows that environmental awareness has gone up since 2000.

The results also suggests that the importance of urban forests and ecosystem services has gained greater recognition and attention in recent years, likely due to the increasing awareness of the benefits they provide to human health and well-being, as well as to the environment (Nowak & Dwyer, 2007). It is also noteworthy to observe that even though there was a decrease in the number of publications in 2022, it still remains relatively high compared to the earlier years of the study period. The results indicates that the topic of urban forests and ecosystem services continues to be a relevant and important area of research, with ongoing contributions from the scientific community.

The United States, China, and Italy are the top three most productive countries in this field, as measured by the number of publications. However, it is important to note that the United States also had the highest number of total citations, indicating that their research has had a significant impact on the field. It is also interesting to see that many countries have a higher number of single country publications (SCP) compared to multiple country publications (MCP), indicating a need for increased collaboration among researchers from different nations in this field of global concern. Furthermore, the case of Sweden, with a high number of citations per article despite a relatively low number of publications, highlights the importance of quality over quantity when evaluating the impact and influence of research. It is important to recognize that a single highly cited article can have a significant impact on the field, regardless of the number of publications or authors from a particular country. Sweden is the country of affiliation of the most cited article in the area since 1996, entitled "Ecosystem services in urban areas" (Bolund & Hunhammar, 1999), with 1543 citations at the time of this publication. The paper is one of the earliest and pioneering works that addressed the concept of ecosystem services specifically in urban areas, analyzing a range of ecosystem services.

It is interesting to see that while the journal "Urban Forestry & Urban Greening" had presented the largest number of articles on the topic of urban forests and ecosystem services, the journal "Landscape and Urban Planning" had a much higher average number of citations per article, indicating that the articles published in the journal are highly influential in the field. Similarly, the journal "Environmental Pollution" had a very high average number of citations per article, despite having a relatively small number of publications on the topic. Therefore, it is important to consider both the number of publications and the impact factor or average number of citations per article when evaluating the quality and impact of a journal in a specific field of study. Even though "Urban Forestry & Urban Greening" does not have the highest number of citations, it is important to observe the trend in Figure 4 regarding the journal, as it has maintained its prominence in publications related to urban forests and ecosystem services for 12 years, consistently publishing a considerably higher number of articles than the other journals. The results indicates that the journal has established itself as a leading venue for research in this field. The analysis of journal productivity and trends is important for understanding the evolution of the field and the major contributors to scientific knowledge in a given area (Donthu et al., 2021). Through the identification of the most influential journals and publications, researchers can better focus their efforts on advancing the state of the art and making meaningful contributions to the field (Oliveira et al., 2019).

The analysis at the author level provides valuable insights into the contributions and impact of researchers within a specific field (Donthu et al., 2021). Our results present the top 10 authors who have made significant contributions to the advancement of knowledge in the area under investigation. Tied for the first place are Escobedo, F. J., and Nowak, D. J., both of whom have published 33 papers in the analyzed period. Our findings show that the 10 authors who contributed most to the scientific development of the area published their first articles from 2006 onwards, ten years after the first publication record for the analyzed keywords. This observation, occurring a decade after the initial publication record for the analyzed keywords, suggests a maturation and consolidation phase in the domain. It is also important to note that the two authors who contributed the most, Escobedo and Nowak, had constant annual productions in the area since 2012.

Our results provide valuable information about the top 10 most cited papers in the field of urban forestry and ecosystem services research. The top 10 papers have significant attention and recognition within the academic community, as reflected by their citation counts ranging from 250 to 1543. The scientist David Nowak appears two times as the lead author in the list of the top 10 most cited articles. The results highlight his significant contribution to the field of urban forestry and ecosystem services research. Another finding that stands out in the list of the top 10 most cited papers is the presence of a recent paper, published by Venter et al. in 2020, in sixth place, with all other papers published between 1999 and 2016. The article discusses and presents that recreational use of green space increased during the COVID-19 outbreak in Oslo, Norway, highlighting an important ecosystem service promoted by urban forests, which allows people to play, rest, and connect with nature: Recreational and cultural values (Bolund & Hunhammar, 1999). According to data from World Health Organization (2022), the pandemic of COVID-19 brought a 25% increase in the prevalence of anxiety and depression worldwide, which tends to lead people to look for more leisure options, and urban green areas can be in great demand for such a purpose.

The findings of the analysis of hot topics provide an overview of the recurring themes and concepts in research related to urban forests and ecosystem services, showcasing the key areas of interest and focus within the field. The term "city" stands out as the most frequently mentioned term in the abstracts of the analyzed articles, indicating the strong focus on urban environments and their relationship with urban forests and ecosystem services. The results suggest that researchers are interested in understanding the specific challenges and opportunities that cities present in terms of incorporating and managing urban forests. The term "ecosystem" is the second most mentioned term, indicating the recognition of the broader ecological context in which urban forests operate and the importance of considering ecosystem processes and functions in urban planning and management. The terms "forest" and "forests" come in third and fourth place, respectively, highlighting the fundamental role of forests, both natural and managed, within urban areas and the recognition of their multiple benefits. The term "green", appearing in fifth place, suggests the focus on the green spaces and vegetation elements within urban environments and their contribution to human well-being, climate regulation, and biodiversity conservation.

The word cloud provides a snapshot of the key themes and concepts within the field of "ecosystem services" and "urban forest" research, showcasing the central role of terms such as "ecosystem services," "urban forest," "urban forestry," and "urban infrastructure" in shaping the discourse and understanding in this area of study. The results indicate that the terms abovementioned are highly relevant and frequently discussed in the research literature, emphasizing the significance of studying the relationship between urban environments and the services provided by natural ecosystems. Additionally, the presence of the term "urban infrastructure" as a commonly used keyword suggests that researchers in this field are interested in exploring the intersection between urban development and the provision of ecosystem services. The study by Romero-Duque et al. (2020), concerning the Latin America and the Caribbean, revealed that the incorporation of urban ecosystem services into urban design is minimal, yet at the same time, it is advancing rapidly in connection with the application of innovative approaches, such as eco-friendly approaches, and in support of the emerging global urban agenda. The results of our paper highlight the recognition of the role that urban planning, design, and infrastructure play in creating and maintaining urban forests and the associated benefits they provide.

Through our analysis of the Sankey diagram, we observe a notable increase in connections between themes over time, indicating a dynamic evolution of research topics. During the process of thematic evolution, we find a substantial number of connections and intensive conversion relationships among the themes. Notably, the term "ecosystem services" consistently appears across all three analyzed periods, establishing connections with "benefits" and "diversity" from 2019 onwards.

The analysis of trend topics used in the abstracts of the analyzed articles from 2011 to 2022 reveals interesting shifts in the most commonly used terms over the years. In 2011, there was a notable prevalence of the terms "soils" and "emissions," indicating a focus on understanding soil-related aspects and emissions in the research. As we move to 2015, the terms previously mentioned continue to be widely used, but additional terms such as "GIS," "scale," "storage," and "impacts" emerge, suggesting an expansion of research areas and interests. The term "ecosystem services" started gaining more frequency in 2018 and reached its peak usage in articles published in 2019. The results suggest an increasing recognition of the importance of studying and understanding the various services provided by ecosystems. From 2019 onwards, we observe the emergence of additional terms such as "governance," "water," and "city" as prominent topics in article abstracts. The mentioned terms become increasingly viewed, with "governance" and "water" reaching their highest frequency in 2021, highlighting the growing attention towards understanding the governance mechanisms and challenges associated with managing water resources in urban settings. Since 2021, the most frequently used terms in article abstracts include "park," "impact," "governance," and "forest", which suggest a continued interest in studying the impacts of various factors on parks and forests, with an ongoing focus on governance aspects. The changing trend topics in the abstracts reflect the evolving research priorities and interests within the field over the analyzed period. It showcases the emergence of new areas of study, the growing recognition of key concepts such as ecosystem services and biodiversity, and the increasing attention towards governance and management of natural resources in urban environments.

In our results, the main motor themes identified include "urban ecosystem", "urban tree" and "tree mortality". The themes have reached a high level of research maturity and represent well-established areas of study within the field (Kim et al., 2021). The main basic themes identified are "ecosystem services", "urban forest" and "urban forestry". While these themes have gained popularity, they are still in the process of achieving full research maturity. The main emerging or declining themes identified in our analysis are "resilience", "ozone" and "trade-offs". The themes indicate areas of research that are currently in a state of flux, with varying levels of activity and research maturity. Finally, the main niche themes identified are "canopy cover", "Canada" and "cemeteries". The themes represent developed but relatively isolated areas of research that may have limited accessibility or focus within the broader research community (Nowell et al., 2017).

2.6 Conclusions

Our results present the findings of an exploratory bibliometric review that examined the evolution of various aspects in the field of urban forests and ecosystem services. It can be inferred that the subject has gained notable scientific attention over the years, likely attributed to the implications of climate change on urban ecosystems and their fragility. When analyzing the results, we can notice that production in the area intensified more from 2011 onward, highlighting the more recent awareness of the benefits that urban forests may provide.

Terms such as "ecosystem services," "urban forest," "urban forestry," and "urban infrastructure" emerge as central themes, emphasizing their relevance and frequency of discussion within the research literature. The visual representation through word clouds and Sankey diagrams provides a comprehensive understanding of the interrelationships and evolution of research themes over time, highlighting the dynamic nature of the field.

Overall, the conclusions of the research paper underscore the growing recognition and importance of studying ecosystem services in urban areas. An important conclusion is that more cross-country contributions are needed on the topics studied. The findings contribute with valuable insights into the scientific environment, showing that articles analyzing the relationship between governance and ecosystem services in urban areas have emerged as the latest publication trend. Our paper also provides collaboration opportunities, research gaps, such as efforts aiming the study of landscape metrics, fragmentation, resilience and trade-offs in urban areas, providing a foundation for future research and decision-making.

3. Chapter 2: With Great Ecosystem Services Comes Great Responsibility: Benefits Provided by urban vegetation in Brazilian Cities

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3.1 Abstract

Ecosystem services, the benefits people receive from the natural environment, are extremely important, specifically in urban areas. Urban forests, even representing a pivotal role in global sustainability, have been converted into different human-modified landscapes. Therefore, this paper aims to analyze the ecosystem services provided by the urban areas of 25 cities of the Atlantic Forest in Brazil. We used the i-Tree Canopy software to classify the land use encountered in these regions. We also quantified the monetary benefits of the urban vegetation and took into account some socioeconomic variables (i.e., total population, population density, Human Development Index (HDI), and Gross Domestic Product (GDP) per capita) to analyze if the ecosystem services or the land uses are associated with this. Our results show that the average impervious area (IN) in urban areas was 47.02%. Blumenau (SC) was the city that presented the highest percentage of trees over pervious places (45.71%). Our data reveal that together, the cities studied sequester a significant total of 235.3 kilotonnes of carbon and substantial 864.82 kilotonnes of CO_2 Equivalent (CO_2 Equiv.) annually. Furthermore, together they also store, through their vegetation, a total of 4861.19 kilotonnes of carbon and 17824.32 kilotonnes of CO_2 Equiv. Porto Alegre, a state capital, presented the highest carbon sequestration and store values. We found out that the average monetary estimate of annual carbon sequestration was $3.57 million, while the average stored estimate was $73.76 million. Pearson's correlogram showed a strong positive correlation between density and the percentage of IN in urban areas ($p < 0.001$). IN was also positively correlated with HDI ($p = 0.01$), indicating that urban areas with higher HDI tend to have larger impervious areas. Therefore, our data suggest essential insights about the ecosystem services provided by urban areas and can serve as significant findings to drive policymakers' attention whether they want to provide more ecosystem services in cities that already have outstanding contributions or in cities that still do not have important contributions.

Keywords: Carbon sequestration. Carbon stock. i-Tree Canopy. Urban forests. Vegetation benefits.

3.2 Introduction

Ecosystem services are the benefits that people receive from the natural environment. They include the provisioning of goods, such as food, timber, and water; the regulation of ecosystem processes, such as air and water quality; and the cultural services, such as recreational and aesthetic value. Even though representing a pivotal role for global sustainability, due to uncontrolled economic development, natural environments have been converted to different human-modified landscapes due to multiple land use purposes, such as increased demand for agricultural land, livestock grazing, mining, energy, and other destination (Arroyo-Rodríguez et al., 2017; Chazdon, 2003; Curtis et al., 2018; Malhi et al., 2014).

In a changing world, conservation efforts are mandatory to pursuit a more sustainable future since trees can provide several valuable benefits to people who live in urban spaces. In this context, ecosystem services are defined by the contribution that ecosystems give to humans, whether directly or indirectly (TEEB, 2010). Ecosystem services can be of a wide range, starting with basic life support systems for humankind (climate and air quality regulation), material goods (food, energy, medicines), and also spiritual, cultural, and recreational uses (IPBES, 2019). In urban landscapes, trees can help maintain hydrological functions, such as precipitation interception, water infiltration, and evapotranspiration, which will reflect on soil moisture, water quality, and erosion mitigation (Nowak et al., 2020).

Therefore, managing biodiversity is one of the main priorities of today, and investigating environmental data is increasingly important for future conservation and preservation purposes. In this way, Geography Information Systems (GIS) works as a strong ally in the area of natural sciences, in order to contribute to the survey and analysis of environmental data with high applicability to promote public policies. As mentioned by Riley & Gardiner (2020), in the past few years a large number of tools have been developed to quantify ecosystem services and their value. One of the most popular and used for urban forests worldwide is the i-Tree platform (https://www.itreetools.org/), a free suite of software programs backed by peer-reviewed research that allows obtaining estimates of the ecosystem services and monetary value of UPFs based on a variety of data collection techniques. For example, the i-Tree Canopy (2021) program uses a methodology to produce a statistically valid estimate of land cover use through aerial images available in Google Maps, and provides some important outputs like the quantity of pollutants removal (and their equivalent monetary value based on USA medical services), the quantity of atmospheric carbon (CO_2 equivalent) removal and the total carbon stocked in the vegetation, as well those monetary values. Then, GIS tools represent unique applications in surveying urban forest, which ecosystem contributions can be estimated in a more rapid and low-cost way (Cimburova & Barton, 2020).

In this context, the carbon market emerges as an essential tool. It is based on tools that aim to limit greenhouse gases and create strategies for a trading system between countries or companies that exceeds those limits and other peers that sell permissions on emissions, called “carbon credits", which come from carbon sequestered by trees, and had a 20% increase in its global market value in 2020, reaching $277 billion (Reuters, 2021), which tends to rise given the efforts that governments and companies are doing in order to achieve ambitious environmental commitments. The mechanisms of the international carbon market were created in 1997 with the Kyoto Protocol as means of meeting greenhouse gas emissions reduction and are composed of three approaches: Clean Development Mechanisms (CDM), which stands for allowing developed countries to meet its emission reduction targets with the implementation of projects in developing countries; Joint Implementation (JI), which countries with emission reduction commitments are allowed to implement projects in another country, that can benefit from its investments; and Emission Trading (ET) which allows the selling of greenhouse gas emissions units from a country that have spare credits to countries that are over their emissions limits, being, then, a new commodity (UNFCCC, 2021).

It is also worth mentioning the Voluntary Carbon Market, which consists of individuals or organizations that buy certificated carbon credits towards a voluntary reduction of the pollutants emissions, and since carbon dioxide is the main greenhouse gas, this compensation is usually simplified as carbon trading, where 1 carbon credit equals 1 ton of carbon sequestered by trees (UNFCCC, 2021; Kreibich & Hermwille, 2021). Currently, several fintech, traditional banks, and investment brokers have negotiated carbon credits in the voluntary market since the number of companies interested in environmental policies has grown in the last years. Furthermore, the carbon market is extremely heated after the implementation of the Paris Climate Agreement in 2015 and tends to increase even more. Then, carbon markets are gaining relevance; for example, the unit of Carbon Emissions Future stocks (CFI2Z1), traded on the London stock exchange, were traded at approximately €24.00 at the beginning of 2020 and in April 2021, is traded at €94.31 (Investing, 2023).

Therefore, considering the incredible biodiversity that Brazilian forests have, even when located in cities, measures for their conservation and protection are crucial for a truly sustainable future. The need for correct environmental management is even more urgent given the various ecosystem services promoted by vegetation, which can greatly benefit human well-being and have significant economic importance. Considering that carbon sequestration and storage are one of the primary ecosystem services today, as they reduce the concentration of greenhouse gases in the atmosphere, more studies should be carried out to promote public policies aimed at mitigating global climate change, which tend to be disastrous for several species, including the human being. Among the mechanisms that support environmental studies and decision-making, GIS is accessible, requires low investments, and, even so, generates accurate products for better urban environmental management. Among GIS tools, i-Tree Canopy stand-out, performing, through satellite images, the estimation of ecosystem services promoted by the vegetation of cities, especially concerning the removal of greenhouse gases, being widely used (Alpaidze & Salukvadze, 2023; Costemalle et al., 2023; Robinson et al., 2021). In this sense, with the global growth trend of carbon markets, such measurements are essential, mainly due to the possible contribution of urban vegetation in the carbon emissions trading market.

Here, we estimate the ecosystem services promoted by the vegetation of the urban area of 25 Brazilian cities of the Atlantic Forest. Therefore, to achieve this objective, the following specific objectives are proposed: (1) To investigate the percentage of distinct classes of the land cover of the studied cities; (2) To estimate annual pollutants and carbon sequestration and carbon stocks by vegetation and its contribution to the mitigation of climate change and the surrounding society; (3) To carry out the economic valuation of such ecosystem services through carbon markets and their future potential for Brazil's green economy; (4) To verify if socioeconomic variables have any relationship with land cover classes and pollutants and carbon sequestration.

3.3 Material and methods

3.3.1 Study area

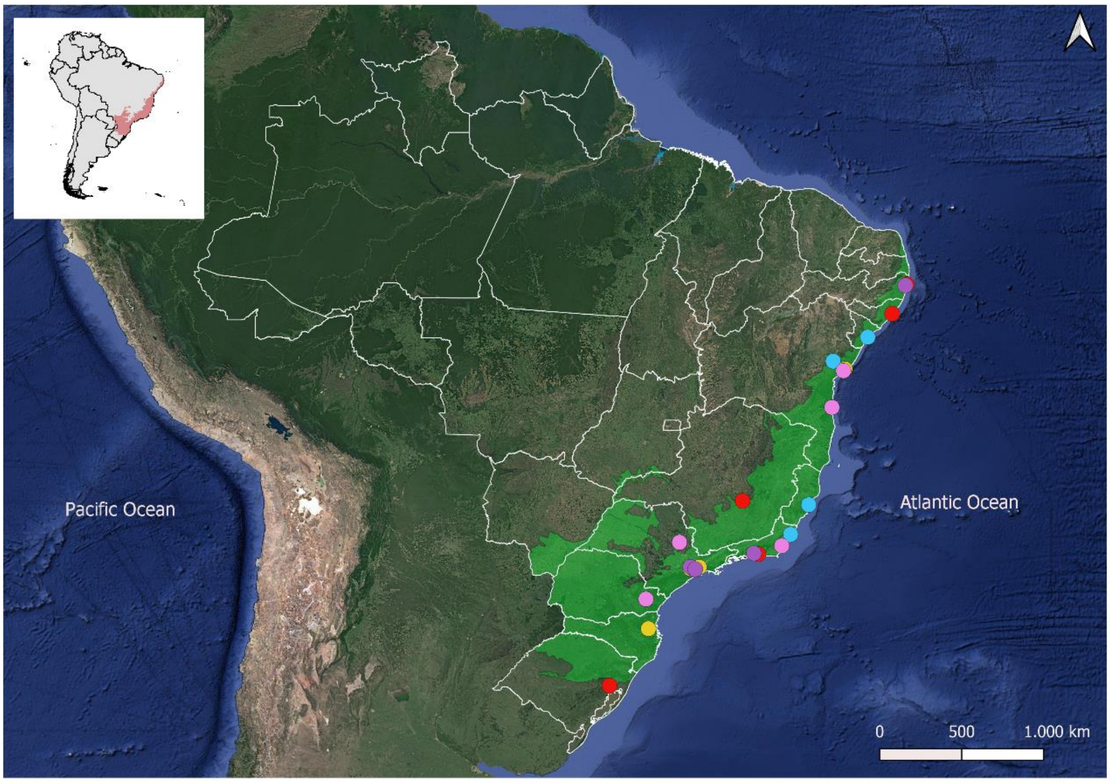
For data collection, we first set a threshold by selecting all 226 cities in the Atlantic Forest with an estimated population of over 100,000 inhabitants in 2020, according to the IBGE (2021), because such regions typically experience significant urban anthropogenic pressures and socioeconomic factors, with major urban expansion processes strongly linked to the decline of urban forests and their ecosystem services (Baines, Wilkes, & Disney, 2020; Bonilla-Bedoya, Mora, Vaca, Estrella, & Herrera, 2020; B. Chen, 2020; G. Chen, Singh, Lopez, & Zhou, 2020). Subsequently, we divided the cities into five groups based on population (Table 5). Then, we randomly selected five cities from each group, resulting in 25 studied cities (Figure 11).

Table 5 – Population classes and cities that had their city center studied for the provision of ecosystem services

Population	Cities
100,000 - 300,000	Leme (SP), Colombo (PR), Macaé (RJ), Simões Filho (BA) e Ilhéus (BA)
300,000 - 500,000	Suzano (SP), Diadema (SP), Taboão da Serra (SP), Blumenau (SC) e Camaçari (BA)
500,000 - 700,000	Campos dos Goytacazes (RJ), Mauá (SP), Aracaju (SE), Feira de Santana (BA) e Serra (ES)
700,000 - 900,000	São Bernardo do Campo (SP), Duque de Caxias (RJ), Osasco (SP), Jaboatão dos Guararapes (PE) e Santo André (SP)
>1 million	Recife (PE), São Gonçalo (RJ), Porto Alegre (RS), Belo Horizonte (MG), Maceió (AL)

Source: Author's own elaboration (2023).

Figure 11 – Distribution of the studied cities. Red dots= cities with more than 1 million inhabitants; Purple dots= cities with 700,000 - 900,000 inhabitants; Blue dots= cities with 500,000 - 700,000 inhabitants; Yellow dots= cities with 300,000 - 500,000 inhabitants; Pink dots= cities with 100,000 - 300,000 inhabitants; Green shadow= Atlantic Forest.



Source: Author's own elaboration (2023).

3.3.2 Tree cover assessment

To assess tree canopy coverage (area and percentage) and classify the land cover in urban areas, we utilized the land classification algorithm tool i-Tree Canopy (2021), which is part of the i-Tree tools suite and is freely distributed by the United States Department of Agriculture. The i-Tree Canopy is a web-based tool that employs the random sampling method, which facilitates efficient data acquisition. Moreover, the vegetation data obtained through i-Tree tools using satellite imagery exhibit a strong correlation ($R^2 = 0.9$) with results obtained via advanced and expensive tools, such as airborne Light Detection and Ranging (LiDAR), as reported by Parmehr et al. (2016).

Since our goal is to evaluate the ecosystem services promoted by the urban area of the studied municipalities, in this study, we used the classification of urbanized areas in Brazilian cities, made available by IBGE (2019). Therefore, the boundaries of the urban areas were cut using the "clip" tool in ArcGIS v 10.6 (ESRI, 2020). We input the ESRI shapefile into i-Tree Canopy. As the program uses an algorithm based on metrics from the USA, for this work, we selected only the American states that have a Köppen climate classification (1923) similar to that found in the Atlantic Forest, to avoid inaccuracies in the results. The American states selected were: Alabama, Arkansas, Florida, Georgia, Louisiana, North Carolina, and Tennessee. Only metrics for urban areas available in the software were considered. This was done for all 25 cities.

After that, we performed a photo-interpretation of the random points generated by the program. We performed the photo-interpretation using high-resolution aerial imagery recorded in 2022 and 2023 from National Center for Space Studies / Airbus satellites made available by Google Earth. We generated random points until we found a standard error ≤2.5%, which measures uncertainty in land cover within the software, for each land cover category. The cover classes used in this study can be found in Table 6.

Table 6 – Land use cover classes assessed for the provision of ecosystem services in 25 Brazilian cities

Item	Cover class	Description
IN	Impervious cover non-plantable no trees	sites where trees are impractical (road, rail, roof, monument)
IP	Impervious cover partially plantable no trees	Sites where trees are possible (sidewalk, parking lot, plaza)
SN	Soil cover non-plantable no trees	Sites where trees are impractical (dirt road)
SP	Soil cover partially plantable no trees	Soil cover partially plantable no trees
SVN	Short Vegetation cover non-plantable no trees	Grasses, herbaceous, or shrubs where trees are impractical (athletic field)
SVP	Short Vegetation cover partially plantable no trees	grasses, herbaceous, or shrubs where trees are possible (backyard)
TEI	Tree Evergreen over Impervious	trees with constant canopy over impervious ground
TEP	Tree Evergreen over Pervious	trees with constant canopy over pervious ground
W	Water	Ocean, estuary, river, lake, wetland, etc
O	Other	areas not captured in above categories

Source: Author's own elaboration (2023).

3.3.3 Ecosystem services

Based on the estimated vegetation cover area provided by i-Tree Canopy, we assessed the following ecosystem services: total carbon sequestered annually in trees; total carbon stored in trees; Carbon Monoxide removed annually; Nitrogen Dioxide removed annually; Ozone removed annually; Sulfur Dioxide removed annually; Particulate Matter less than 2.5 microns removed annually and Particulate Matter greater than 2.5 microns and less than 10 microns removed annually. Carbon and carbon equivalent estimations are presented in kilotonnes (kt), while the other parameters are presented in tons (t).

3.3.4 Monetary valuation of ecosystem services

With the analysis of satellite images, the program measures certain ecosystem services facilitated by urban vegetation while estimating the monetary value of ecosystem services and their significance to the community (Nowak et al., 2018). The developers of the software used various metrics related to the costs of pollution impacts on human health, such as reduced productivity, hospital admissions, and mortality, to achieve one of the goals of this study - the monetary valuation of air pollutant removal, including CO_2 Equivalent (Nowak et al., 2014). Valuing ecosystem services requires consideration of various factors, including healthcare and labor legislation. In Brazil, we have a Universal Health Care system called the Unified Health System (SUS) that differs from the American Healthcare System, and we also have unique labor legislation. Therefore, to estimate ecosystem services economically, we used an alternative approach of equivalent carbon dioxide (CO_2 Equiv.) values based on the carbon credit market, as proposed by Costemalle et al. (2023), which fits better in the Brazilian reality. Then, we utilized values from the 'CFI2Z1-Future Carbon Credit' market. For this, we consider the value of CFI2Z1 recorded on April 18, 2023 (€94.31). The values were later converted into dollars following the exchange rate of the same day (1 euro= 1.0971 dollars).

3.3.5 Socioeconomic and population data

Since socioeconomic and population factors, such as wealth and population density, may correlate with the greater or lesser provision of green areas in cities (Chen et al., 2022; Richards et al., 2017; Wu & Kim, 2021), we collected the following data from IBGE's "Cities" portal (2023): total population, population density (Km^2), Human Development Index, and Gross Domestic Product per capita (R$).

3.3.6 Data Analysis

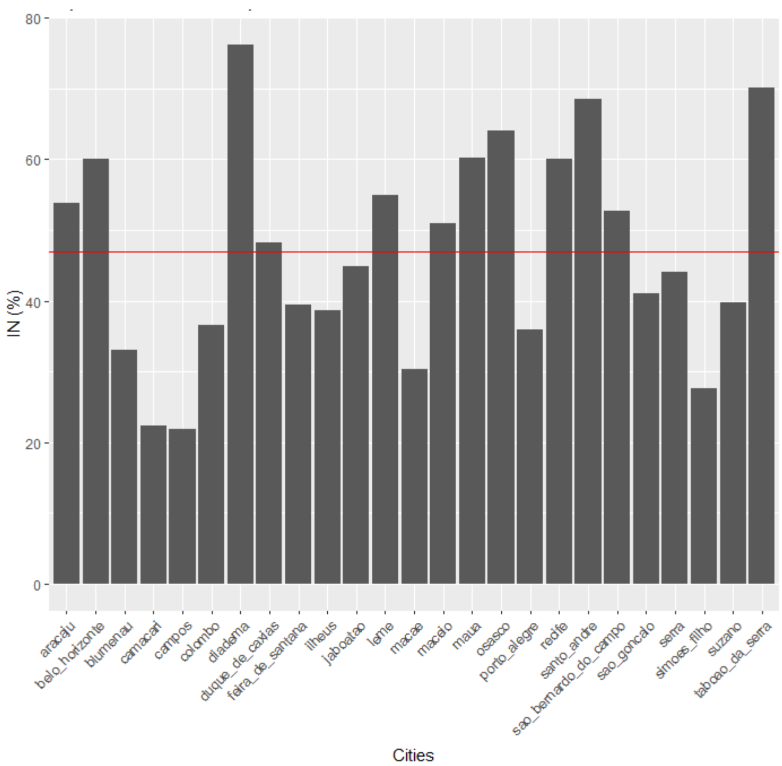
We conducted a correlation analysis to investigate the relationships between several factors, including the HDI, total population, population density, GDP, and various pollution parameters estimated using the iTree Canopy tool. To analyze the correlations, we used the Pearson algorithm. We visualized the results through ggcorrplot package (Kassambara, 2019) in R software (R Core Team, 2023). Then, the trends were analyzed using scatterplots also in R (R Core Team, 2023), using the Kendall method.

3.4 Results

3.4.1 Land cover

Our results show that the dominant land cover class was “Impervious cover non-plantable no trees” (IN), with 80% of the cities studied having IN as the dominant land cover in the urban area. The average impervious area in urban areas was 47.02% (Figure 12). IN values varied from 22.37% in Camaçari, in the state of Bahia, to 76.21% in Diadema, a city in the metropolitan region of São Paulo (Table 3).

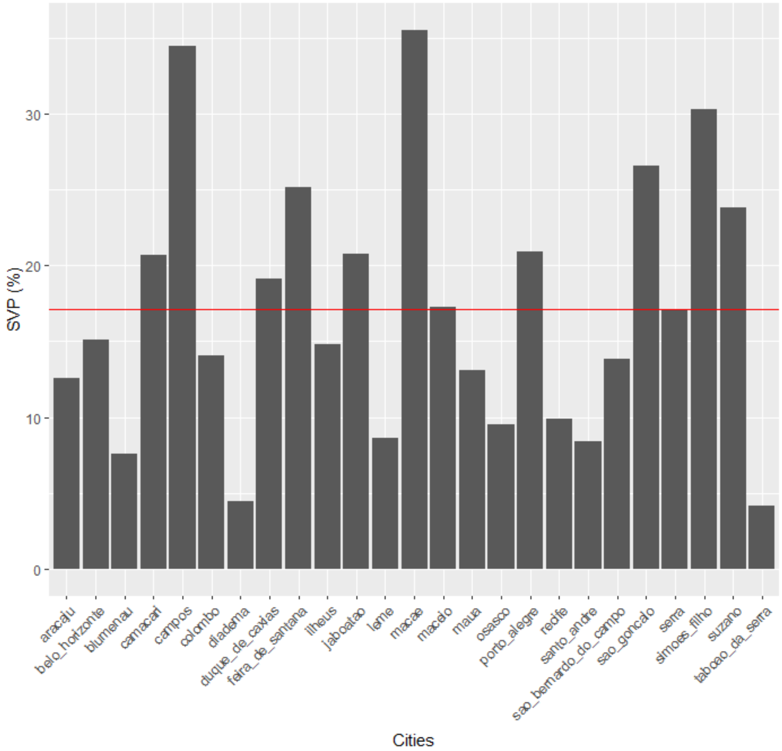
Figure 12 – Impervious cover non-plantable no trees (IN) percentages in the city center of the studied cities. Red line represents the average value



Source: Author’s own elaboration (2023).

The cities of Campos dos Goytacazes, in Rio de Janeiro state, Simões Filho, in Bahia state, and Macaé, in Rio de Janeiro state, presented “Short Vegetation cover partially plantable no the trees” (SVP) as the dominant cover class in their central regions, with 34.44%, 30.27%, and 35.52% respectively (Figure 13).

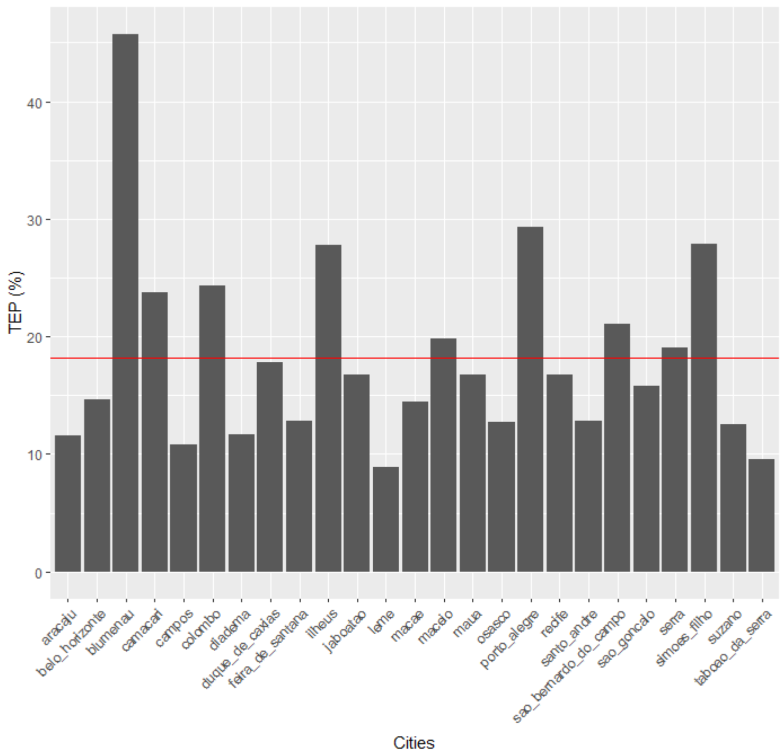
Figure 13 – Short Vegetation cover partially plantable no trees (SVP) percentages in the city center of the studied cities. Red line represents the average value



Source: Author’s own elaboration (2023).

Blumenau, located in the state of Santa Catarina, is the only city in which the "Tree Evergreen over Pervious" cover class dominates, accounting for 45.71% of the urban areas. The average presented for the "Tree Evergreen over Pervious" cover class was 18.20% (Figure 14). Table 7 illustrates the other land cover classes and their percentage variation through the cities.

Figure 14 – Tree Evergreen over Pervious (TEP) percentages in the city center of the studied cities. Red line represents the average value



Source: Author’s own elaboration (2023).

Table 7 – Cover classes (%) found in the studied cities. IN= Impervious cover non-plantable no trees; IP= Impervious cover partially plantable no trees; SN= Soil cover non-plantable no trees; SP= Soil cover partially plantable no trees; SVN= Short Vegetation cover non-plantable no trees; SVP= Short Vegetation cover partially plantable no trees; TEI= Tree Evergreen over Impervious; TEP= Tree Evergreen over Pervious; W= Water, and O= Other

City	IN	IP	OTH	SN	SP	SVN	SVP	TEI	TEP	W	TEI+TEP
Aracaju (SE)	53.9	0.25	1.26	3.53	12.85	0.5	12.59	0.76	11.59	2.77	12.35
Belo Horizonte (MG)	60.05	4.44	2.87	0	1.04	1.04	15.14	0	14.62	0.78	14.62
Blumenau (SC)	33.08	1.01	3.28	1.77	5.81	0	7.58	0.51	45.71	1.26	46.22
Camaçari (BA)	22.37	1.02	4.75	1.36	24.42	0	20.68	1.02	23.73	0.68	24.75
Campos dos Goytacazes (RJ)	21.94	1.11	3.33	4.17	18.89	0.28	34.44	1.94	10.83	3.06	12.77
Colombo (PR)	36.49	2.7	4.59	1.08	16.22	0.27	14.05	0	24.32	0.27	24.32
Diadema (SP)	76.21	1.72	2.07	0	2.41	0	4.48	1.03	11.72	0.34	12.75
Duque de Caxias (RJ)	48.24	1.01	2.51	1.51	6.28	1.01	19.1	1.51	17.84	1.01	19.35
Feira de Santana (BA)	39.37	2.1	4.2	3.41	10.5	0.52	25.2	1.31	12.86	0.52	14.17
Ilhéus (BA)	38.62	2.38	5.56	0.53	3.97	0.53	14.81	0	27.78	5.82	27.78
Jaboatão dos Guararapes (PE)	44.81	2.28	2.78	2.53	6.33	0.51	20.76	2.03	16.71	1.27	18.74
Leme (SP)	54.94	1.52	7.85	0.51	16.2	1.01	8.61	0	8.86	0.51	8.86
Macaé (RJ)	30.33	1.91	4.92	0.82	9.84	0.27	35.52	0.27	14.48	1.64	14.75
Maceió (AL)	50.88	2.76	4.26	1	1.25	0.75	17.29	1	19.8	1	20.8
Mauá (SP)	60.21	1.57	0.79	2.36	4.71	0	13.09	0.26	16.75	0.26	17.01
Osasco (SP)	64.13	5.16	1.9	0.27	2.72	0.27	9.51	2.99	12.77	0.27	15.76
Porto Alegre (RS)	35.87	3.53	1.63	0.54	4.08	0.82	20.92	2.45	29.35	0.82	31.8
Recife (PE)	60.05	2.35	0.78	0.78	4.18	0.52	9.92	3.13	16.71	1.57	19.84
Santo André (SP)	68.6	2.91	0.29	1.16	3.2	0	8.43	2.03	12.79	0.58	14.82
São Bernardo do Campo (SP)	52.76	0.75	2.51	2.01	3.02	0.75	13.82	0.25	21.11	3.02	21.36
São Gonçalo (RJ)	41.09	6.2	4.65	1.29	1.81	1.29	26.61	1.29	15.76	0	17.05
Serra (ES)	44.02	0.25	3.56	3.31	10.43	0.25	17.05	0.76	19.08	1.27	19.84
Simões Filho (BA)	27.6	0.89	6.53	0	5.93	0	30.27	0	27.89	0.89	27.89
Suzano (SP)	39.79	1.05	4.97	2.62	13.61	0	23.82	0.52	12.57	1.05	13.09
Taboão da Serra (SP)	70.15	3.58	2.69	0	7.76	0	4.18	1.79	9.55	0.3	11.34
Average	**47.02**	**2.17**	**3.38**	**1.46**	**7.89**	**0.42**	**17.11**	**1.07**	**18.20**	**1.23**	**19.28**
Coeficient of Variation (%)	**31.81**	**68.81**	**55.03**	**84.29**	**77.72**	**93.80**	**50.58**	**88.66**	**44.94**	**102.41**	**41.62**

Source: Author's own elaboration (2023).

3.4.2 Pollutants removal

Our data reveal that about 5739.66 tons are sequestered annually by vegetation in the cities studied. The city of Taboão da Serra (SP) presented the lowest values for the sequestration of pollutants in this study. On the other hand, surprisingly, Porto Alegre (RS), a state capital, presented the highest amounts for pollutant sequestration annually (Table 8).

Carbon monoxide (CO) sequestered annually varied from 0.35 tons in Taboão da Serra (SP) to 15.67 tons in Porto Alegre. The average amount of CO sequestered annually among the cities studied is 4.08 tons.

Concerning the results found for nitrogen dioxide (NO_2), the amount sequestered annually ranged from 1.37 to 60.48 tons. The overall average was 15.75 tons. Regarding the amount of ozone (O_3) sequestered annually, our data range from 13.14 to 580.21 tons, averaging 151.20 tons. The annual sulfur dioxide (SO_2) sequestration varied between 0.74 and 32.86 tons. The average presented was 8.56 tons.

The values of particulate matter removed less than 2.5 microns ($PM_{2.5}$) annually ranged from 0.69 to 30.67 tons. With respect to particulate matter greater than 2.5 microns and less than 10 microns (PM_{10}) removed annually, we had a range between 3.65 and 161.1 tons.

Table 8 – Pollutants removed annually by the vegetation of the studied cities. CO= carbon monoxide; NO_2= nitrogen dioxide; O_3= ozone; SO_2= sulfur dioxide; $PM_{2.5}$= particulate matter removed less than 2.5 microns; PM_{10}= particulate matter greater than 2.5 microns and less than 10 microns and t= tons

City	CO(t)	NO_2(t)	O_3(t)	SO_2(t)	$PM_{2.5}$(t)	PM_{10}(t)
Aracaju (SE)	2.31	8.9	85.42	4.84	4.51	23.72
Belo Horizonte (MG)	7.46	28.8	276.27	15.65	14.6	76.71
Blumenau (SC)	13.32	51.39	492.95	27.92	26.05	136.87
Camaçari (BA)	9.21	35.53	340.8	19.3	18.01	94.62
Campos dos Goytacazes (RJ)	4.61	17.6	170.72	9.67	9.02	47.4
Colombo (PR)	2.71	10.47	100.44	5.69	5.31	27.89
Diadema (SP)	0.57	2.21	21.26	1.20	1.12	5.90
Duque de Caxias (RJ)	5.53	21.32	204.53	11.58	10.81	56.79
Feira de Santana (BA)	3.73	14.38	137.95	7.81	7.29	38.3
Ilhéus (BA)	1.22	4.69	45.03	2.55	2.38	12.5
Jaboatão dos Guararapes (PE)	2.93	11.29	108.32	6.14	5.72	30.07
Leme (SP)	0.41	1.59	15.33	0.86	0.81	4.25
Macaé (RJ)	1.87	7.21	69.14	3.92	3.65	19.2
Maceió (AL)	4.72	18.2	174.56	9.89	9.23	48.47
Mauá (SP)	1.41	5.42	52.03	2.95	2.75	14.45
Osasco (SP)	1.61	6.2	59.47	3.37	3.14	16.51
Porto Alegre (RS)	15.67	60.48	580.21	32.86	30.67	161.1
Recife (PE)	4.64	17.9	171.7	9.73	9.07	47.67
Santo André (SP)	1.88	7.27	69.75	3.95	3.69	19.37
São Bernardo do Campo (SP)	3.41	13.15	126.13	7.14	6.67	35.02
São Gonçalo (RJ)	4.6	17.74	170.23	9.64	9	47.26
Serra (ES)	4.34	16.75	160.71	9.1	8.49	44.62
Simões Filho (BA)	1.95	7.51	72	4.08	3.81	19.99
Suzano (SP)	1.68	6.48	62.13	3.52	3.28	17.25
Taboão da Serra (SP)	0.35	1.37	13.14	0.74	0.69	3.65
Average	**4.08**	**15.75**	**151.20**	**8.56**	**7.99**	**41.98**
Coeficient of Variation (%)	**93.33**	**93.39**	**93.34**	**93.35**	**93.36**	**93.35**

Source: Author's own elaboration (2023).

3.4.3 Carbon sequestration

Together, the cities studied sequester a significant total of 235.3 kilotonnes of carbon and substantial 864.82 kilotonnes of CO_2 Equivalent (CO_2 Equiv.) annually. Furthermore, together they also store, through their vegetation, a total of 4861.19 kilotonnes of carbon and 17824.32 kilotonnes of CO_2 Equiv. Once again, the city of Taboão da Serra presented the lowest values in all parameters sampled. Porto Alegre recorded the highest values for the carbon and

CO_2 Equiv. parameters. The average of carbon sequestered annually was 9.41 kilotonnes per city and 34.59 kilotonnes of CO_2 Equivalent. For each city, the average carbon stocked by the vegetation was 194.44 kilotonnes, while the average CO_2 Equiv values stored were 712.97. All the parameters analyzed, for all cities, can be found in Table 9 and a way to visualize them graphically is present in Figure 15.

Table 9 – Carbon and CO_2 Equivalent estimations for Brazilian cities studied. CO_2 Eq= CO_2 Equivalent

Cities	Carbon (kt)	CO_2 Eq (kt)	Carbon stock (kt)	CO_2 Eq stock (kt)
Aracaju (SE)	5.32	19.5	109.85	402.78
Belo Horizonte (MG)	17.2	63.06	355.27	1302.64
Blumenau (SC)	30.69	112.52	633.91	2324.33
Camaçari (BA)	21.21	77.79	438.25	1606.9
Campos dos Goytacazes (RJ)	10.63	38.97	219.54	804.99
Colombo (PR)	6.25	22.92	129.15	473.56
Diadema (SP)	1.32	4.85	27.35	100.27
Duque de Caxias (RJ)	12.73	48.68	263.01	964.37
Feira de Santana (BA)	8.59	31.49	177.39	650.45
Ilhéus (BA)	2.8	10.28	57.91	212.32
Jaboatão dos Guararapes (PE)	6.74	24.72	139.29	510.72
Leme (SP)	0.95	3.5	19.72	72.31
Macaé (RJ)	4.3	15.78	88.91	326.01
Maceió (AL)	10.87	39.84	224.48	823.08
Mauá (SP)	3.24	11.88	66.91	245.33
Osasco (SP)	3.7	13.57	76.48	280.43
Porto Alegre (RS)	36.12	132.43	746.12	2735.78
Recife (PE)	10.69	39.19	220.8	809.58
Santo André (SP)	4.34	15.92	89.7	328.89
São Bernardo do Campo (SP)	7.85	28.79	162.2	594.73
São Gonçalo (RJ)	10.6	38.85	218.9	802.64
Serra (ES)	10	36.68	206.67	757.78
Simões Filho (BA)	4.48	16.43	92.59	339.51
Suzano (SP)	3.87	14.18	79.89	292.93
Taboão da Serra (SP)	0.81	3.01	16.90	61.99
Average	**9.41**	**34.59**	**194.44**	**712.97**
Coeficient of Variation (%)	**93.37**	**93.23**	**93.34**	**93.34**

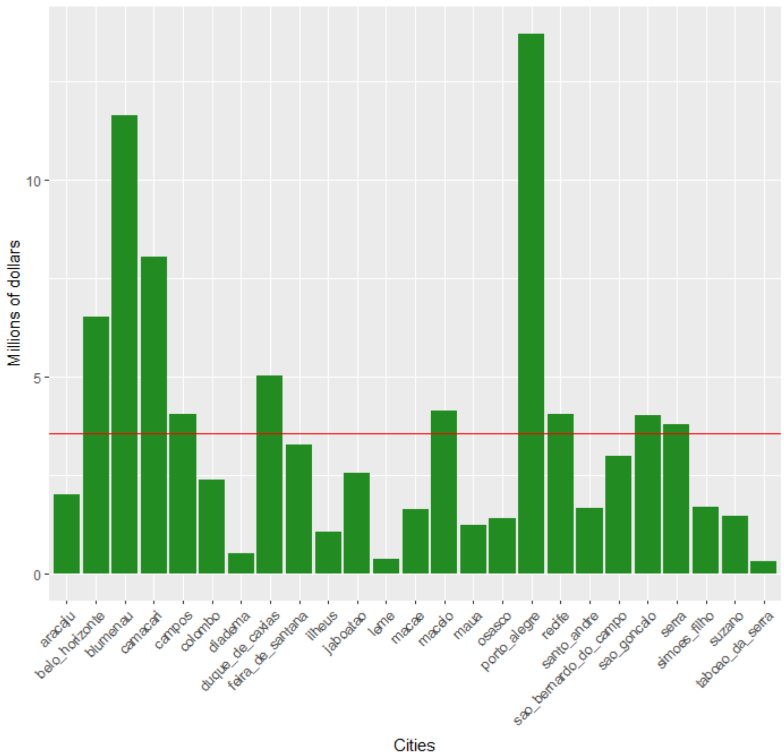
Source: Author’s own elaboration (2023).

3.4.4 Monetary measurement

When it comes to the monetary estimate of the ecosystem services promoted by the 25 cities studied, together, they are estimated to contain a total of US$1.8 billion in carbon credits stocked, sequestering a total of more than US$89 million in carbon credits annually.

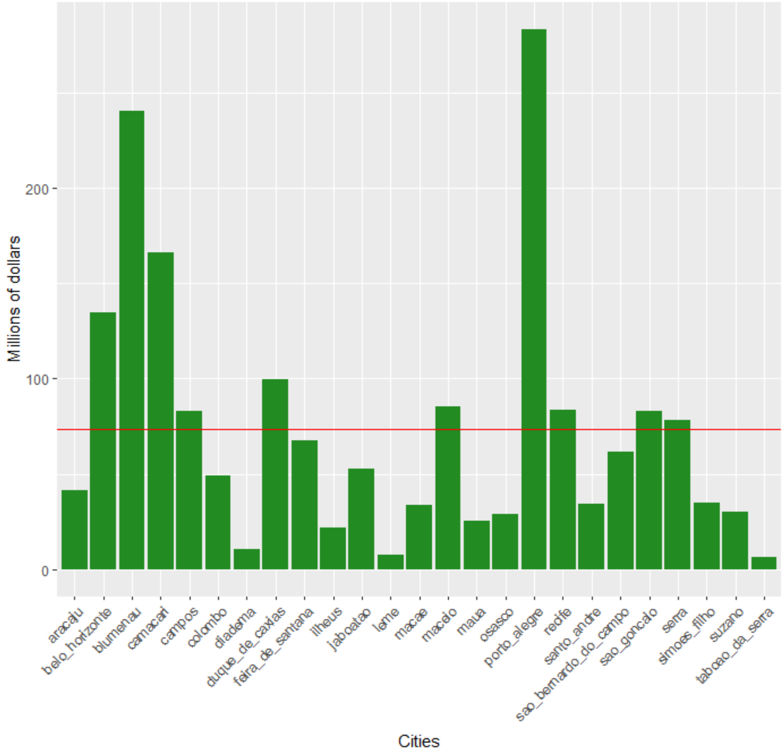
Again, our data points to the city of Taboão da Serra (US$ 0.3 million sequestered annually; US$ 6.4 million stocked) as having the lowest potential values to be applied in carbon credits and the city of Porto Alegre (13.7 million sequestered annually; 283 million stocked) as having the highest values, mirroring previous results (Figures 15 and 16). The average monetary estimate of annual carbon sequestration was 3.57 million, while the average stored estimate was $73.76 million. Detailed values for each city can be seen in Table 10.

Figure 15 – Monetary estimate of the annual CO_2 sequestration realized by the vegetation of the city center of the studied cities



Source: Author’s own elaboration (2023).

Figure 16 – Monetary estimate of the total CO_2 stocked in the vegetation of the city center of the studied cities



Source: Author's own elaboration (2023).

Table 10 – Monetary estimation of the amount of CO_2 Equivalent sequestered annually and the amount of CO_2 Equivalent stocked in the vegetation of the cities studied. The values are in dollars

City	Sequestred (US$)	Stocked (US$)
Aracaju (SE)	2,017,616.25	41,674,639.65
Belo Horizonte (MG)	6,524,660.55	134,780,904.20
Blumenau (SC)	11,642,163.10	240,492,614.30
Camaçari (BA)	8,048,736.83	166,261,925.80
Campos dos Goytacazes (RJ)	4,032,128.48	83,290,302.83
Colombo (PR)	2,371,475.1	48,998,069.30
Diadema (SP)	501,817.37	10,374,686.23
Duque de Caxias (RJ)	5,036,797.90	99,780,952.98
Feira de Santana (BA)	3,258,191.58	67,300,435.38
Ilhéus (BA)	1,063,645.90	21,968,219.60
Jaboatão dos Guararapes (PE)	2,557,716.60	52,842,921.60
Leme (SP)	362,136.25	7,481,734.92
Macaé (RJ)	1,632,717.15	33,731,439.68
Maceió (AL)	4,122,145.20	85,162,029.90
Mauá (SP)	1,229,193.90	25,383,681.78
Osasco (SP)	1,404,053.98	29,015,391.03
Porto Alegre (RS)	13,702,201	283,064,317.20
Recife (PE)	4,054,891.33	83,765,218.65
Santo André (SP)	1,647,202.60	34,029,426.08
São Bernardo do Campo (SP)	2,978,829.33	61,535,226.28
São Gonçalo (RJ)	4,019,712.38	83,047,154.20
Serra (ES)	3,795,187.90	78,405,602.15
Simões Filho (BA)	1,699,971.03	35,128,250.93
Suzano (SP)	1,467,169.15	30,308,734.78
Taboão da Serra (SP)	310,505.96	6,413,950.32
Average	**3,579,234.67**	**73,769,513.18**
Coeficient of Variation (%)	**93.22**	**93.63**

Source: Author's own elaboration (2023).

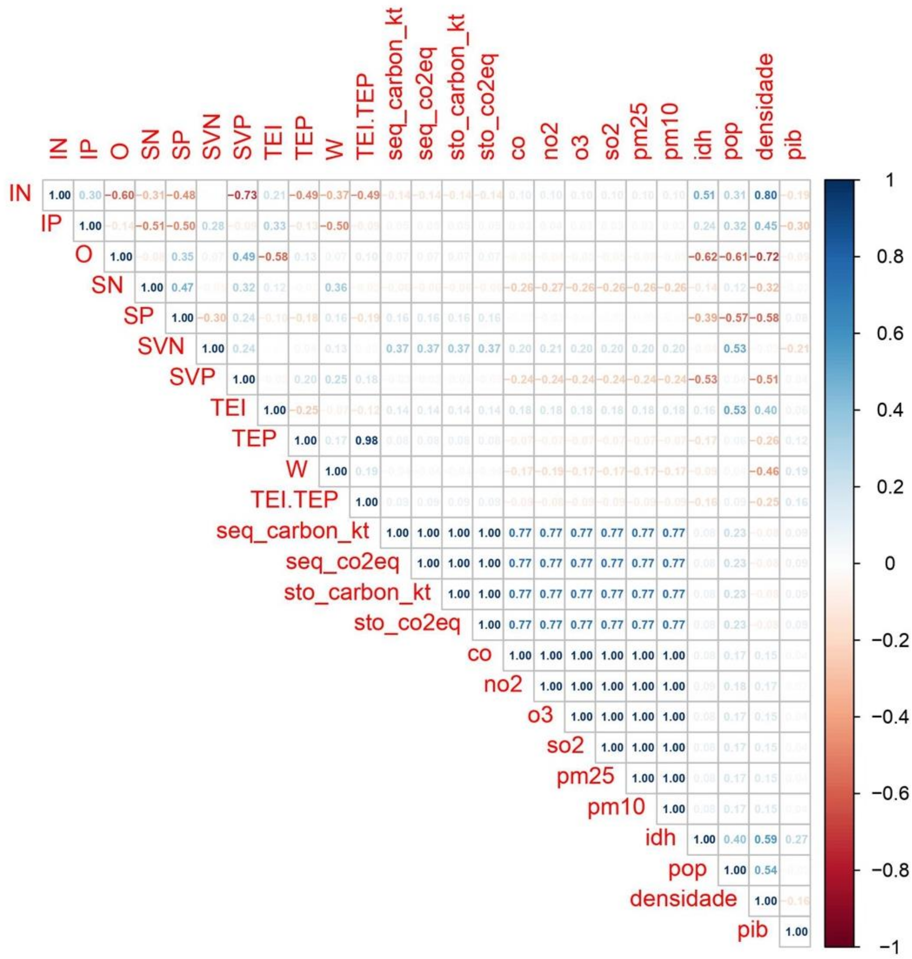
3.4.5 Variables correlations

After conducting a Spearman's correlation analysis, the correlogram showed a strong positive correlation between density and the percentage of impervious areas (IN) in urban areas ($p < 0.001$) (Figures 17 and 18). IN was also positively correlated with HDI ($p = 0.01$), indicating that urban areas with higher HDI tend to have larger impervious areas. The cover classes and socioeconomical variables that are highly correlated are presented in figure 18.

Our results also show a positive correlation between population and “short vegetation non-plantable no trees” (SVN) ($p < 0.01$), indicating that the increase in population influences the amount of this class. A negative relationship is also shown between “short vegetation cover partially plantable no trees” (SVP) and HDI ($p < 0.01$). SVP shows a negative correlation with HDI ($p < 0.05$).

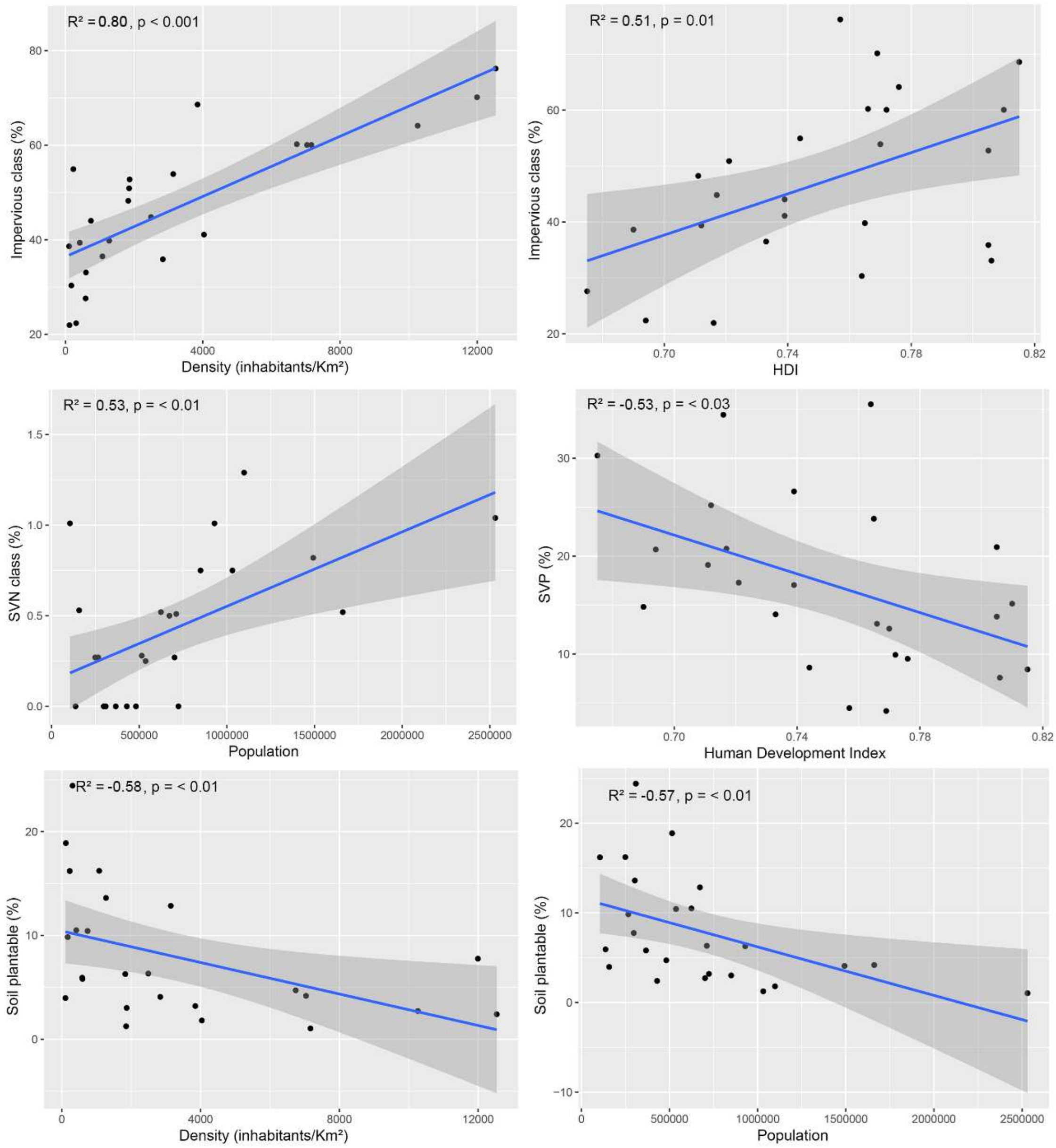
Our findings indicate a negative correlation between the amount of “soil cover partially plantable no trees” (SP) in urban areas and both population density and total population ($p<0.01$). The results suggest that as population and density increase, there are fewer areas available for planting new trees.

Figure 17 – Correlation analysis chart between land cover classes, pollutants, and socioeconomic variables



Source: Author’s own elaboration (2023).

Figure 18 – Simple linear regression plots with the relationships between land cover classes and socioeconomic variables



Source: Author’s own elaboration (2023).

3.5 Discussion

In this study, we analyzed, in urban areas, the cover classes’ relationships with socioeconomic variables and the contributions in pollutant removal by the urban vegetation of several cities. Our findings demonstrate that, in most of the cities, the urban areas provide valuable ecosystem services to the human population and biodiversity. Therefore, our study underscores the importance of urban vegetation in promoting environmental sustainability and improving the quality of life in urban areas. We found that more than 235,000 tons of carbon is sequestered annually, and more than 4 million tons are stored in the vegetation of the studied cities. Furthermore, regarding CO_2 Equiv., about 864,000 tons of this pollutant are sequestered annually, and more than 17 million tons are stored in trees. The remarkable results show that vegetation can substantially impact climate change mitigation and improve air quality (Demuzere et al., 2014; Gómez-Villarino et al., 2020).

Another important finding is related to the great economic potential that urban trees can mean regarding carbon credits. Even though our study was conducted only in urban areas, which may be tiny in smaller cities, it points to great economic potential, which can serve as data for decision-makers to conserve and prioritize investment in green infrastructure and to inform urban planning and policy. The average values of the estimated annual sequestration exceed 3 million dollars when considering only the urban area of the studied municipalities. Furthermore, the average estimated values for the carbon that is stored in the vegetation are more than 73 million dollars. The finding that urban trees have great economic potential in terms of carbon credits is expressive as it provides an incentive for decision-makers to invest in green infrastructure and prioritize urban tree conservation.

It is interesting to note that even though the average results for annual sequestration and carbon stock were lower compared to the results found in an urban study in the city of Naples, Italy (Oliveira et al., 2022), our average study area (urban area of each municipality) is much smaller than the 1200 Km^2 studied by the Italians, who measured about $24 million in annual sequestration and $530 million for the carbon stored in trees. It is worth mentioning that, besides having a different total area, the economic measurement of the Italian study and the present research was also different.

The results of our analysis show that the dominant land cover class in the urban areas of the Brazilian cities studied is “Impervious cover non-plantable no trees” (IN), with 80% of the cities having IN as the dominant land cover. The findings are consistent with research showing that urbanization is often associated with increases in impervious surfaces, such as roads, parking lots, and buildings, which can negatively impact ecosystem services and urban biodiversity (Feng et al., 2021; Strohbach et al., 2019). It is particularly concerning that the values of IN varied widely across the cities studied, ranging from 22.37% in Camaçari to 76.21% in Diadema. The results suggest that some cities may be more vulnerable to the negative impacts of impervious surfaces than others, and that targeted efforts may be needed to address this issue. One potential solution for reducing the negative impacts of impervious surfaces in urban areas is to increase the amount of urban green space, including trees and other vegetation.

Some cities, like Campos dos Goytacazes, Macaé, and Simões Filho presented SVP as the most dominant land cover in the urban areas. Our findings are particularly interesting because they demonstrate that above mentioned cities have large areas that can potentially serve for planting arboreal vegetation, which tend to promote a greater amount of ecosystem services related to pollutant sequestration and carbon stock when compared to short vegetation, and can have significant benefits for public health, air quality, and climate change mitigation. It is worth noting, however, that planting and maintaining urban trees can be challenging, particularly in areas with high levels of impervious surfaces or other competing land uses (Bodnaruk et al., 2017; Oldfield et al., 2013). As such, any efforts to increase urban tree cover in these cities, preferably with native and non-invasive species, should be accompanied by careful planning and management, as well as community engagement and education (Butt et al., 2021). Our finding states that Blumenau is the only city where the dominant cover class is "Tree Evergreen over Pervious", which is particularly noteworthy because it highlights the potential for other cities in Brazil to increase their urban tree cover and promote sustainable urban development.

Our data indicate that the amount of CO_2 sequestered by vegetation in urban areas can vary greatly between cities, with Porto Alegre and Blumenau standing out as particularly effective areas for carbon sequestration, which can be due to the fact that these two cities have the largest quantity of vegetation in their urban areas. The variation in CO_2 sequestration rates between cities may be due to a variety of factors, including differences in vegetation coverage, types of vegetation, and environmental conditions. Therefore, this information underscores the importance of protecting and promoting urban green spaces for their role in carbon sequestration and mitigating the impacts of climate change, but we also highlight that proper planning for these urban areas is mandatory for the vegetation to achieve its potential (Wang et al., 2021). It is also important to note that while the average amount of CO_2 sequestered annually among the cities studied is 59.89 tons, this may not be representative of all cities. The variation in the amount of CO_2 sequestered by urban vegetation in different cities highlights the importance of local factors in determining the effectiveness of urban green space for pollutant sequestration (Wang et al., 2021). Factors such as the type, structure, and density of vegetation, the amount of impervious surfaces in the city, the level of vehicular traffic, and spatial pattern optimization of urban green space can all have significant impacts on the ability of urban vegetation to absorb pollutants like CO_2 (Liu et al., 2023).

Overall, our findings regarding the amount of carbon and CO_2 sequestered annually by urban vegetation in Brazilian cities are significant for understanding the role that urban green spaces have in cities. By investing in urban green space and promoting sustainable urban development, cities can harness the power of nature to improve the welfare of their residents, while also contributing to global efforts to mitigate the impacts of climate change (Kolimenakis et al., 2021). The variation in pollutant sequestration between cities is likely due to a combination of factors, such as differences in land cover, vegetation type and density, and local emissions sources. Taboão da Serra has a higher proportion of impervious surfaces, such as roads and buildings, compared to other cities in the study (70.15%) which could limit the amount of vegetation cover and, therefore, the capacity for pollutant sequestration. In contrast, Porto Alegre may have more vegetation cover and probably a more diverse range of vegetation types that are effective at sequestering pollutants. Additionally, the city has implemented policies and programs, such as a Master Plan for Urban Forestry, to promote the planting and maintenance of urban trees and other vegetation (Prefeitura Municipal de Porto Alegre, 2007).

The results of the study show that urban vegetation plays an important role in sequestering pollutants. NO_2 is a toxic component of urban air that can cause several respiratory problems (Kwiatkowski et al., 2021). It is mainly produced by fossil fuel combustion, particularly in transportation, electricity generation, and industrial and residential activities (Jarvis et al., 2010; Restrepo, 2021). Therefore, cities with higher levels of vehicular traffic or industrial activity may have higher levels of NO_2 emissions, which could affect the capacity of vegetation to sequester this pollutant. In contrast, cities with lower levels of traffic and industrial activity may have fewer NO_2 emissions, which could increase the effectiveness of vegetation in sequestering this pollutant. O_3 is a pollutant that is formed in the atmosphere through the reaction of nitrogen oxides (NOx) and volatile organic compounds (VOCs) in the presence of sunlight (Finlayson–Pitts & Pitts, 2000). Therefore, the capacity of vegetation to sequester O_3 may be influenced by factors such as the abundance and types of vegetation, the intensity and duration of sunlight, and the levels of NOx and VOCs in the atmosphere, which have increased in urban areas due to vehicles (Notario et al., 2012).

The removal of particulate matter (PM) by vegetation is a critical ecosystem service provided in urban areas (Han et al., 2020). The results of this study suggest that vegetation in urban areas of the cities studied can effectively remove both $PM_{2.5}$ and PM_{10}, which are known to have adverse effects on human health and the environment, specifically because the presence of particulate matter (PM) in the air presents a greater risk to human health compared to ground-level ozone and other commonly found air pollutants, such as carbon monoxide (Kim et al., 2015). The removal of $PM_{2.5}$ and PM_{10} by vegetation can occur through a variety of mechanisms, including dry deposition, interception, and absorption (Beckett et al., 1998; Diener & Mudu, 2021). Vegetation can capture and retain particles through the physical structure of leaves and branches, as well as through the uptake of particles by stomata and the absorption of particles through the leaf surface (Li et al., 2019; Li et al., 2022). The range of values found for $PM_{2.5}$ and PM_{10} removal in this study reflects differences in the abundance and quality of vegetation in the urban areas studied, as well as differences in local sources of PM emissions. Cities with higher levels of vehicular traffic or industrial activity may have higher levels of PM emissions, which could affect the capacity of vegetation to remove these pollutants (Shan et al., 2020).

The positive correlation between density and IN could be explained by the fact that cities with higher density tend to have more buildings and less available space for vegetation, resulting in larger impervious areas (McDonald et al., 2023; Mumm et al., 2022), which could negatively impact the provision of ecosystem services, such as air quality regulation and carbon sequestration, as impervious surfaces prevent water infiltration into the soil and reduce the ability of trees and other vegetation to absorb pollutants and store carbon. The positive correlation between IN and HDI could be attributed to the fact that cities with higher HDI tend to be larger (Sheth & Bettencourt, 2023), which can result in a greater proportion of impervious surfaces. However, the positive correlation may also indicate a potential trade-off between urban development and the provision of ecosystem services, as more developed areas tend to have a higher demand for infrastructure and may prioritize economic development over environmental considerations. Overall, the results suggest that urban planning and management strategies should consider the potential trade-offs between urban development and the provision of ecosystem services, and aim to balance economic, social, and environmental objectives. Strategies such as green infrastructure planning, green roofs, and urban forests can help mitigate the negative impacts of impervious surfaces and increase ecosystem services in urban areas.

The findings highlight the importance of considering urban population dynamics in the context of carbon management strategies. Our findings highlight the challenges of urban greening and the importance of considering the availability of suitable planting spaces in urban planning. As cities continue to grow and populations increase, there is a greater need for green spaces to enhance the quality of life of urban residents and mitigate the negative impacts of urbanization. However, the limited availability of soil for planting new trees can make it challenging to achieve this goal. Therefore, policymakers and urban planners need to consider innovative approaches to create new green spaces.

3.7 Conclusions

Our results show that the amount of carbon, CO_2 Equivalent, and other pollutants sequestered and stored by urban vegetation can vary greatly between cities and is influenced by factors such as the amount of vegetation present, total population, population density, and land use patterns. The results of the average of pollutants sequestered annually and stored among the cities studied provides a useful benchmark for assessing the effectiveness of urban green space in different cities. Cities with lower amounts of pollutants sequestered may want to consider strategies for increasing the amount of urban vegetation, while cities with higher amounts may want to build on their existing green space to further promote the ecosystem services provided by trees and other vegetation. The fact that the city of Taboão da Serra consistently presented the lowest values for all parameters sampled suggests that there may be opportunities for this city to increase the amount of vegetation present in its urban areas, potentially leading to greater ecosystem service provision. On the other hand, the city of Porto Alegre, which had the highest values for the carbon and CO_2 Equiv. parameters, may be seen as an example of how urban vegetation can provide significant benefits in terms of carbon storage and pollutant sequestration. By highlighting the variation in ecosystem services provided by urban vegetation across different cities, the study provides important insights for policymakers and urban planners seeking to promote urban greening initiatives.

4. Chapter 3: How Climate Change Might Affect Brazilian Urban Forests?

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*Submitted to “Urban Forestry & Urban Greening”.

4.1 Abstract

Urban forests play a critical role in the health and livability of cities. Global climate change is having significant and wide-ranging impacts on the Earth's climate and weather patterns. Here, we examine how climate change might affect Brazilian urban forests. Through photo interpretation, we found 6739 urban forest fragments from the 326 cities with a population greater than 100,000 inhabitants. Then, we modelled, using generalized additive model (GAM), generalized linear models (GLM), Maxent, and Random Forest (RF) models, the possible impacts of climate change in urban forests for each Brazilian Biome. Our findings show that climate change, even in more optimistic scenarios, may severely impact the environmental suitability of urban forests in all biomes, that is, the climate will not be suitable anymore for the urban forest types that are now present in the areas studied. The results are expected especially in the Atlantic Forest and Cerrado, two biodiversity hotspots. The two most affected phytogeographic domains house most of the Brazilian human population, one of which tends to suffer substantial impacts. We also warn that Brazilian urban forests can be drastically affected, having their composition extremely modified and their biodiversity may diminish and even face homogenization. Therefore, urgent mitigation and adaptation actions are needed to tackle climate change.

Keywords: Brazilian forests; global warming; species distribution model; urban areas.

4.2 Introduction

Urban forests play a critical role in mitigating the negative impacts of urbanization by providing a host of ecological, social, and economic benefits, including acting as carbon sinks (Alpaidze & Salukvadze, 2023; Costemalle, Candido, & Carvalho, 2023). Urban forests also provide other benefits such as improved air quality, reduction of the urban heat island effect, reduction of stormwater runoff, and provision of recreational opportunities (Endreny, 2022). However, urban forests also face many challenges, such as climate change, urbanization, and development, which can lead to the loss of forested areas and the degradation of existing forests (Li & Zhao, 2015). Consequently, it is crucial to protect and enhance urban forests in order to maximize their carbon sequestration potential and other benefits.

Temperature and precipitation pattern change is likely to lead to severe modification in the structure of forests (Kirilenko & Sedjo, 2007), particularly the ones that are closer to the cities. Data from the Sixth Report from Intergovernmental Panel on Climate Change (2022) point to a significant increase in the global average temperature in projections, taking into account different scenarios, from optimistic to pessimistic, ranging from 0.3°C to 4.8°C by 2100, which can strongly influence the distribution and patterns of urban forests in tropical regions. Concerning precipitation, Northern Brazil is likely to experience increased rainfall during the rainy season, which may lead to flooding and landslides, Northeast tends to increase the occurrence of droughts, and the southeast, where most of Brazil's major cities are located, there is likely to be an increase in the frequency and intensity of extreme precipitation events, which may increase the risk of flooding and landslides (IPCC, 2013). Hence, changes in temperature and precipitation, together with other factors, might have results in the environmental suitability, which is the conditional probability of occurrence of a species given the state of the environment at a location (Drake & Richards, 2018), being also defined as the set of needs that a species require to establish itself in a determined ecosystem. Several studies have shown the future predicted impacts of climate change in a wide range of ecosystems and organisms (Bohora Schlickmann et al., 2020; Conedera et al., 2021), which might cause significant loss of biodiversity and, consequently, of the ecosystem services that trees provide to the citizens. Esperon-Rodriguez et al, (2022) showed a tendency to increase the temperature of urban forests in the Brazilian regions studied, besides of the high risk that tree and shrubs in these areas may be exposed. Overall, climate change is a major global challenge that requires urgent action to mitigate its negative impacts and protect the planet for future generations.

Ecological niche modelling has emerged as a trend in predicting the expected impacts of climate change (Gilani, Arif Goheer, Ahmad, & Hussain, 2020; John et al., 2020; Torun &

Altunel, 2020). Niche modelling can also be used to identify areas that are at risk of losing biodiversity due to climate change or other human impacts. In Tanzania, other study that applied niche modelling to ecosystems in a landscape, was found that climate change will threaten forests communities even in the most optimistic scenarios (John et al., 2020). In this context, niche modelling, as well as other conservation and protection strategies for natural areas, such as protected areas, land use planning and ecological monitoring, are important tools for maintaining biological diversity and ecosystem services. In a changing world, conservation efforts, such as trees maintenance, monitoring trees health and community engagement, are mandatory to pursue a more sustainable future since trees can provide several valuable benefits to people who live in urban spaces (Turner-Skoff & Cavender, 2019).

In view of the above-mentioned background, the objectives of this study are: (1) To examine how climate change might affect the distribution of the current Brazilian urban forests; (2) to map the urban forest fragments in the municipalities with more than 100 thousand inhabitants in Brazil; (3) to perform climate modelling for 2050 and 2070 of each of the six Brazilian biomes using the Representative Concentration Pathways (RCPs) 4.5 and 8.5 scenarios; (4) calculate the percentage of contribution of the bioclimatic variables to the generated model for current environmental suitability and (5) verify the estimated amount of area gain or loss of area that is environmental suitable for the present biome or ecosystem type in urban forests.

4.3 Methods

4.3.1 Study area

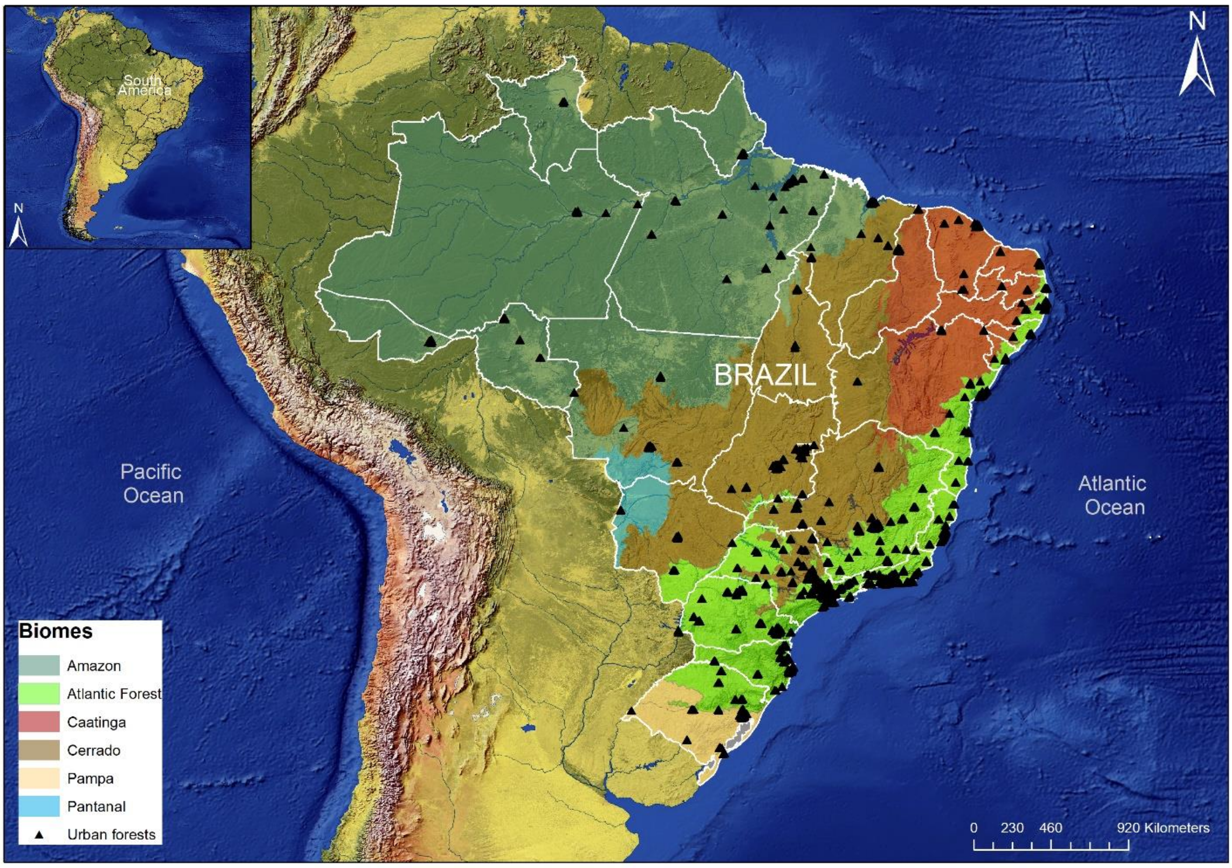
Brazil holds an exceptional biodiversity and ecosystems heterogeneity and occupies a strategic position in the South America region. We considered the entire Brazilian territory, which is continental, with about 8.5 million km², and comprises six distinct biomes, with several different phytophysiognomies, i.e., vegetation types with different physical and structural features (IBGE, 2021). The urban forests studied were located in six phytogeographic domains: Amazon, Atlantic Forest, Caatinga tropical dry forest, Cerrado tropical savanna, Pampa grasslands and Pantanal wetlands.

Since the biomes have a wide range of climatic conditions, we decided to model each biome separately. The Amazon region has an average temperature that varies between 24°C and 27°C, with precipitation between 1750mm and 3000mm annually (IBGE, 2014; Wittmann & Junk, 2016). The Atlantic Forest, because of its great longitudinal vastness, also has varying temperatures, usually between 18°C to 28°C and precipitation ranging from about 1,500 to 3,000 mm, depending on the location within the forest. In some areas, particularly coastal regions, precipitation can exceed 4,000 mm per year (Coutinho, 2016; INMET, 2023). The average temperature of the Caatinga varies between 26°C and 28°C and the precipitation between 200 to 800 mm per year whereas Cerrado presents between 22°C and 27°C and a precipitation that varies from 600 to 2200 mm annually (Coutinho, 2016 INMET, 2023). The Pampa temperature generally ranges between 18°C and 22°C and the precipitation varies between 1200 to 1600 mm (Roesch et al., 2009). The Pantanal wetlands presents an average of 24°C and a precipitation between 1000 and 1250 mm (Marengo et al., 2016).

4.3.2 Urban forests occurrences acquisition

All 326 Brazilian cities with an estimated population greater than 100,000 inhabitants (IBGE, 2020) were considered for data collection, since socioeconomic factors and high urban expansion processes have a strong relationship with the decrease of urban forests and their ecosystem services (Baines, Wilkes, & Disney, 2020; Bonilla-Bedoya, Mora, Vaca, Estrella, & Herrera, 2020; B. Chen, 2020; G. Chen, Singh, Lopez, & Zhou, 2020). Therefore, in each city, we collected the occurrence data for all existing urban forests through photointerpretation using Sentinel-2, Level-2A (L2A), Bottom-of-Atmosphere data (BOA) (ESA, 2020) in Google Earth Engine (Gorelick et al., 2017). All forest fragments ≥ 0.5 ha that are in contact with urbanized areas, i.e. sites with high population size and density, were considered as an urban forest and, therefore, a record. A total of 6.739 urban forests records were collected (Figure 19). We used ArcGis 10.3 (ESRI, 2020) in all data preparation and results visualization. The maps with the environmental suitability generated for current and future predictions were visual analysed to determine which current urban forest fragments might be in danger in the future.

Figure 19 - Location map of Brazilian urban fragments analyzed (black triangles) in the Amazon, Atlantic Forest, Caatinga, Cerrado, Pampa, and Pantanal.



Source: Author's own elaboration (2023).

4.3.3 Bioclimatic Variables

To visualize how climate changes could impact the Brazilian urban forests, we assume that urban forests environmental suitability is considerably affected by bioclimatic variables (temperature and precipitation) and that climate models can help predict species distribution in climate change scenarios (Hijmans & Graham, 2006). Therefore, historical datasets related to 19 bioclimatic variables between 1970-2000 were collected on the WorldClim v. 1.4 database (Hijmans, Cameron, Parra, Jones, & Jarvis, 2005) using a 2.5 minutes resolution (~5km^2). The bioclimatic variables were clipped to the area extent of each biome. In order to avoid multicollinearity, for each biome, using the 'usdm' package on R (R Core Team, 2022), we exclude highly correlated variables detected by variance inflation factor (VIF) statistics, retaining, therefore, only variables with a VIF $\leq$ 10 (Naimi, Hamm, Groen, Skidmore, & Toxopeus, 2014), which avoids adverse effects in the analysis. After this, we conducted the analysis considering only nine variables for the Amazon; seven variables for the Atlantic Forest; nine variables for the Caatinga; eight variables for the Cerrado; seven variables for the Pampa; and four variables for the Pantanal (Table 11). Some variables are included for almost all domains, being the most common used in the modelling processes: Mean Diurnal Range (bio2), Isothermality (bio3), Mean Temperature of Wettest Quarter (bio8), Mean Temperature of Driest Quarter (bio9), Precipitation of Warmest Quarter (bio18), and Precipitation of Coldest Quarter (bio19). We used the same resolution and variables for current and future climate projections in each biome.

Table 11 - Bioclimatic variables used for each biome.

Biome	Code	Variable
Amazon	bio2	Mean Diurnal Range
	bio4	Temperature Seasonality
	bio5	Max Temperature of Warmest Month
	bio8	Mean Temperature of Wettest Quarter
	bio12	Annual Precipitation
	bio14	Precipitation of Driest Month
	bio15	Precipitation Seasonality
	bio18	Precipitation of Warmest Quarter
	bio19	Precipitation of Coldest Quarter
Atlantic Forest	bio2	Mean Diurnal Range
	bio3	Isothermality
	bio8	Mean Temperature of Wettest Quarter
	bio13	Precipitation of Wettest Month
	bio17	Precipitation of Driest Quarter
	bio18	Precipitation of Warmest Quarter
	bio19	Precipitation of Coldest Quarter
Caatinga	bio2	Mean Diurnal Range
	bio3	Isothermality
	bio8	Mean Temperature of Wettest Quarter
	bio9	Mean Temperature of Driest Quarter
	bio12	Annual Precipitation
	bio14	Precipitation of Driest Month
	bio15	Precipitation Seasonality
	bio18	Precipitation of Warmest Quarter
	bio19	Precipitation of Coldest Quarter
Cerrado	bio2	Mean Diurnal Range
	bio3	Isothermality
	bio8	Mean Temperature of Wettest Quarter
	bio12	Annual Precipitation
	bio13	Precipitation of Wettest Month
	bio17	Precipitation of Driest Quarter
	bio18	Precipitation of Warmest Quarter
	bio19	Precipitation of Coldest Quarter
Pampa	bio2	Mean Diurnal Range
	bio4	Temperature Seasonality
	bio8	Mean Temperature of Wettest Quarter
	bio9	Mean Temperature of Driest Quarter
	bio10	Mean Temperature of Warmest Quarter
	bio14	Precipitation of Driest Month
	bio18	Precipitation of Warmest Quarter
Pantanal	bio3	Isothermality

	bio6	Min Temperature of Coldest Month
	bio8	Mean Temperature of Wettest Quarter
	bio9	Mean Temperature of Driest Quarter

Source: Author's own elaboration (2023).

4.3.4 Climate Scenarios

For future predictions, we selected the two following IPCC Representative Concentration Pathways (RCP): RCP 4.5 (Intermediate greenhouse gas emissions scenario) and RCP 8.5 (High greenhouse gas emissions scenario) for the years 2050 (2041–2060 average) and 2070 (2061–2080 average) (IPCC, 2014). Three Global Climate Models (GCMs) were used for predictions: Community Climate System Model version 4 (CCSM4), Hadley Centre Global Environment Model version 2 (HadGEM2-ES), and Model for Interdisciplinary Research On Climate version 5 (MIROC5), since a multi-GCM approach is highly recommended in order to decrease uncertainty and to cover the entire range variation in the models in the multimodel ensemble Coupled Model Intercomparison Project5 (CPMI5) (Taylor, Stouffer, & Meehl, 2012; Goberville, Beaugrand, Hautekeete, Piquot, & Luczak, 2015; Deb, Phinn, Butt, & McAlpine, 2017). After generation the models from the distinct GCMs, we constructed an ensemble model for the current environmental suitability and for each RCP. We also produced binary rasters (suitable/unsuitable) to verify whether the future predictions in the distinct scenarios will show retraction/expansion based on the area (km^2).

4.3.5 Forests distribution modelling methods

Here, we used a species distribution modelling approach to check how climate change will affect forest habitats in different biomes, as made by John et al. (2020), for forest fragments in Tanzania. Four modelling methods were tested in the analysis, namely: a generalized additive model (GAM); generalized linear model (GLM); maximum entropy (Maxent) and random forest (RF). For this, we used the "sdm" package (Naimi & Araújo, 2016) on R (R Core Team, 2022). The algorithms estimate the probability of distribution together with the variables to be analysed, therefore looking for combinations of similar variables in other climatic scenarios, to determine the environmental suitability of Brazilian urban forests in each biome (Phillips & Dudík, 2008; Phillips, Anderson, Dudík, Schapire, & Blair, 2017). We ran ten-fold cross-validation replicates for all the models, with 5000 iterations. We used 70% of the points as training data, and 30% of the points were used to test the model. We used default settings for all other parameters. To determine the contribution of each variable, we used the "varImp" function in “sdm” package (Naimi & Araújo, 2016). To calculate the omission rate of the model, it is necessary to use a threshold or cutoff limit (thresholded), and its choice should maximize the agreement between the observed and predicted distribution of the species, besides meeting the research purposes (Liu et al. 2005). Based on a threshold (value), the continuous probability maps are converted into binary maps of the possible presence (1) or absence (0) of the species. For this step, we selected the best threshold value indicated for presence and absence data, maxSSS (Maximizing the sum of sensitivity and specificity) (Liu et al. 2013; Liu et al. 2016).

4.3.6 Evaluation of the model performance

The generated models were evaluated by observing the values of Area Under the Curve (AUC) of the receiver operating characteristic (ROC). AUC varies from 0 to 1 and the threshold value of 0.8 was considered acceptable, indicating high predictive accuracy, like previous studies have shown (Merow, Smith, & Silander, 2013; Dhyani, Kadaverugu, & Pujari, 2020; Mungi, Qureshi, & Jhala, 2020; Sun et al., 2020). We also used the true skill statistic (TSS) value computed for each model to evaluate the SDMs’ performances and all models with a TSS value greater than 0.6, either obtained for all algorithms were retained (Allouche et al., 2006).

4.4 Results

4.4.1 Model performance

The distribution models had a very good performance, since they were better than random expectation and the average values were considered acceptable. The results (Table 12) indicate the reliability of the models performed for all six biomes in explaining the changes that might occur in Brazilian urban forests in the future due to climate change.

Table 12 – AUC and TSS scores for the six biomes in four different modelling methods. GAM= Generalized Additive Model; GLM= Generalized Linear Model; AUC= Area under the curve; TSS= True skill statistic.

Biome		Model method			
		GAM	GLM	Maxent	Random Forest
Amazon	AUC	0.96 ± 0.01	0.81 ± 0.01	0.94 ± 0.009	1 ± 0.003
	TSS	0.85	0.6	0.79	0.96
Atlantic Forest	AUC	0.85 ± 0.008	0.79 ± 0.008	0.83 ± 0.01	0.98 ± 0.004
	TSS	0.76	0.69	0.6	0.9
Caatinga	AUC	0.96 ± 0.009	0.83 ± 0.01	0.97 ± 0.008	1± 0.004
	TSS	0.92	0.6	0.87	0.98
Cerrado	AUC	0.91 ± 0.008	0.82 ± 0.001	0.90 ± 0.009	0.99 ± 0.003
	TSS	0.74	0.6	0.72	0.93
Pampa	AUC	0.98 ± 0.007	0.85 ± 0.01	0.98 ± 0	0.99 ± 0.004
	TSS	0.94	0.6	0.89	0.96
Pantanal	AUC	0.93 ± 0.08	0.94 ± 0.03	0.99 ± 0.01	0.98 ± 0.03
	TSS	0.86	0.78	0.94	0.97

Source: Author's own elaboration (2023).

4.4.2 Key bioclimatic variables

Based on the results provided, different bioclimatic variables are important for predicting the impacts of climate change on urban forests in different biomes in Brazil. In both the Amazon and Cerrado, precipitation was the main driver of urban forest occurrence. The Amazon presented the Precipitation of the Warmest Month (33% of contribution to the model) and the Precipitation of the Driest Month (11.5%) as the most important factors. In the Cerrado, the Annual Precipitation (16.1%) and the Precipitation of the Wettest Month (15.5%) were the main bioclimatic variables. In the other biomes, the bioclimatic variables that most contributed to the current model generated are, almost all, related to temperature. In the Atlantic Forest, the Mean Diurnal Range (34.1%) and the Precipitation of the Driest Quarter (18.5%) were the most determinant variables. In the Caatinga, the Mean Diurnal Range (27.9%) and the Precipitation of the Coldest Quarter (13.4%) were the variables that most contributed to the models. Mean Diurnal Range and Temperature Seasonality contributed the most to the models, 34.2 % and 23.4% to the Pampa models, respectively. Lastly, Pantanal urban forests models had the Minimum Temperature of Coldest Month (47.8%) and Mean Temperature of Wettest Quarter (43.9%) as the variables that most contributed to the models.

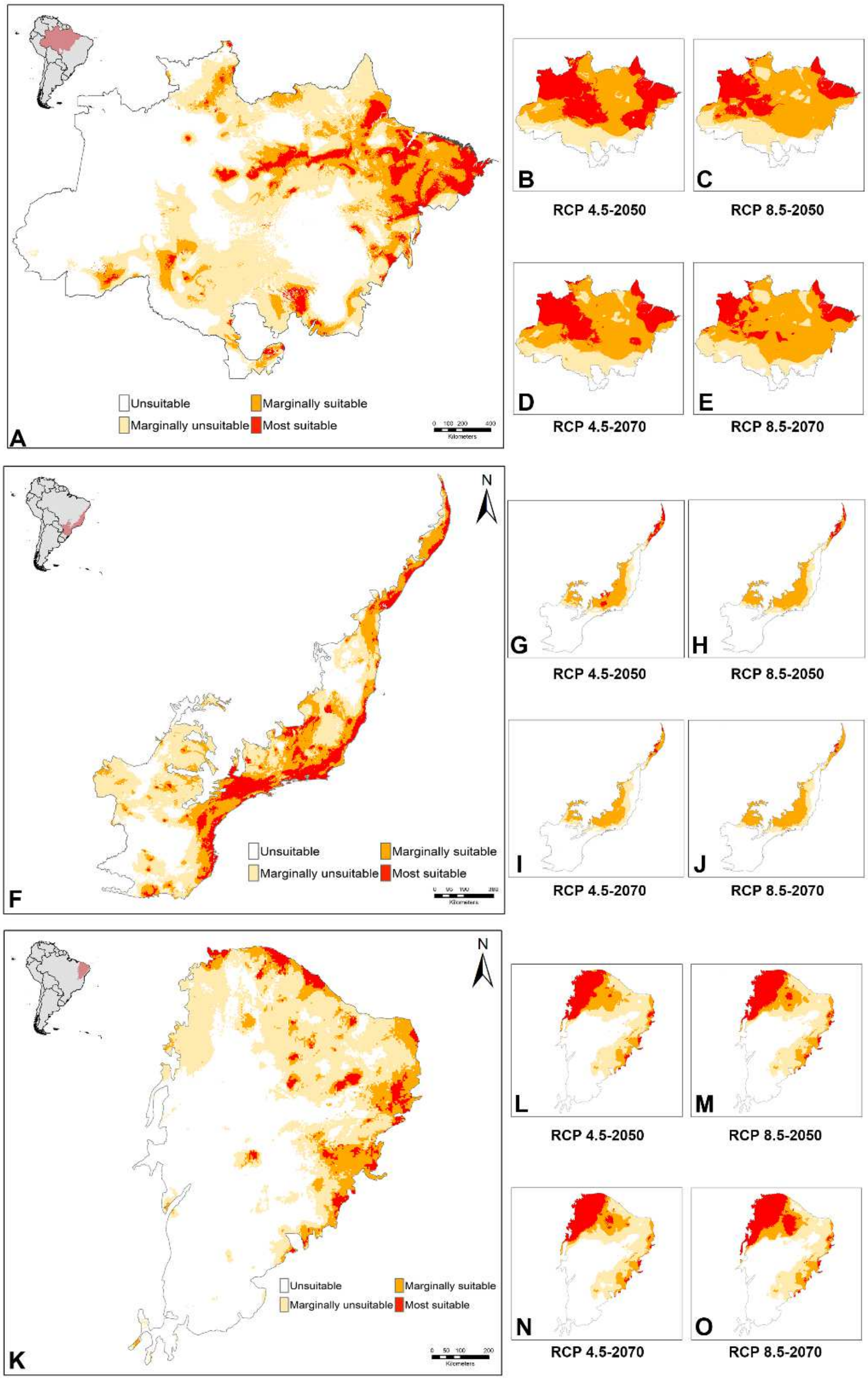
4.4.3 Suitability area change

The visual analysis of the future climate change impacts show that all models predict a certain amount of change in the suitability area of Brazilian urban forests for all six biomes. The biome that tends to have the strongest impacts in the future is the Atlantic Forest (Figures 20 A-E). In figure 2oB, we can observe the loss of environmental suitability of the current (Figure 20A) scenario, even in the most optimistic scenario, RCP 4.5, for 2050. In this scenario, the most extremely affected areas belong to the southeast coast, but other critical results can also be found in inland regions of the southern Atlantic Forest. The results for the most pessimistic scenarios for 2050 show a tendency for environmental suitability to disappear in these inland areas in the biome. Regarding the scenarios for 2070 (Figures 20D and 20E), both optimists and pessimists scenarios predict devastating impacts, since the loss of environmental suitability also advances to most of the country's northeastern coast.

Likewise, concerning the Cerrado (Figures 21 A-E), we can also observe severe loss of suitability areas. The predictions in all scenarios point to decline of urban forests throughout the southern region of the biome, precisely in areas where the Cerrado is closest to the Atlantic Forest, such as in the São Paulo and Minas Gerais states. The Caatinga biome (Figures 21 K-O) may also experience alarming changes in its climate suitability for urban forests. Most of the changes are concentrated in northern parts, especially in the biome's central region, located in the states of Bahia, Piauí, Pernambuco, Paraíba, and southern Ceará.

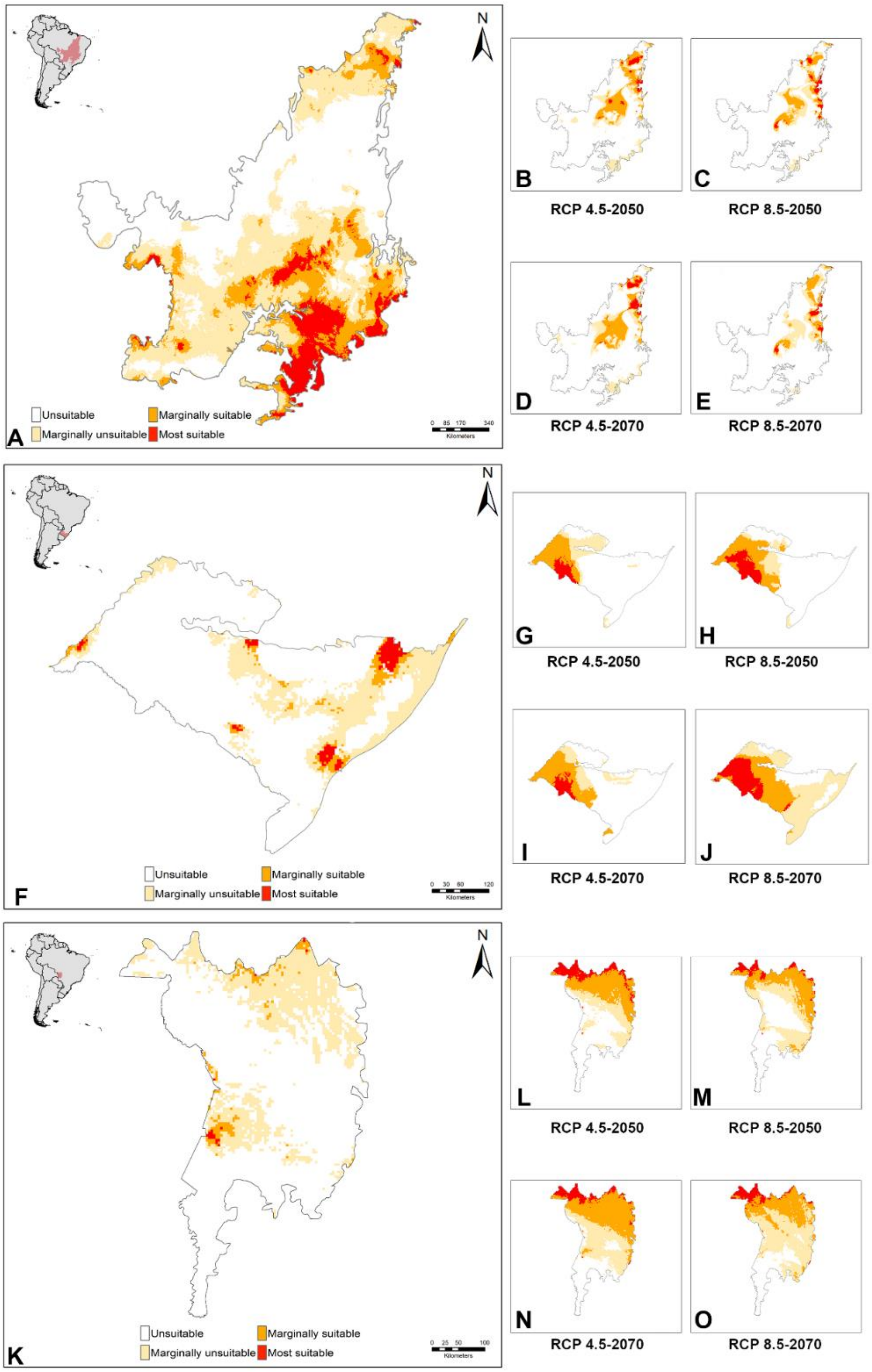
Our results show that almost all studied urban forests in the Pampa (Figures 21 F-J) are likely to range contraction already in the RCP 4.5 scenario in 2050, a fact that remains the same in the following scenarios, apart from RCP 8.5 in 2070. As shown in figures 21 K-O, Pantanal tends to lose suitability of the southern forests. The Amazon tends to conserve more of its central urban forests in the face of future climate change (Figures 21 A-E), although it loses suitability in almost all of its south, and part of the northeast of the biome.

Fig. 20 – Environmental suitability for urban forests from Amazon under current conditions (20A) and in the future in optimistic scenarios in 2050 and 2070 (20B;20D) and pessimistic scenarios in 2050 and 2070 (20C;20E), respectively. Predicted environmental suitability for urban forests from Atlantic Forest under current conditions (20F) and in the future in optimistic scenarios in 2050 and 2070 (20G;20I) and pessimistic scenarios in 2050 and 2070 (20H;20J), respectively. Predicted environmental suitability for urban forests from Caatinga under current conditions (20K) and in the future in optimistic scenarios in 2050 and 2070 (20L;20N) and pessimistic scenarios in 2050 and 2070 (20M;20O), respectively.



Source: Author's own elaboration (2023).

Fig. 21 - Environmental suitability for urban forests from Cerrado under current conditions (21A) and in the future in optimistic scenarios in 2050 and 2070 (21B;21D) and pessimistic scenarios in 2050 and 2070 (21C;21E), respectively. Predicted environmental suitability for urban forests from Pampa under current conditions (21F) and in the future in optimistic scenarios in 2050 and 2070 (21G;21I) and pessimistic scenarios in 2050 and 2070 (21H;21J), respectively. Predicted environmental suitability for urban forests from Pantanal under current conditions (21K) and in the future in optimistic scenarios in 2050 and 2070 (21L;21N) and pessimistic scenarios in 2050 and 2070 (21M;21O), respectively.



Source: Author's own elaboration (2023).

4.4.4 Predicted urban forests distribution

The climate scenarios predicted a change of distribution of the urban forests in all six Brazilian biomes. Although some scenarios indicate a gain of suitability in some cases, it just represents areas with similar bioclimatic variables to those we studied. Here, we focus on the losses of current areas of urban forests. The Atlantic Forest urban forests models showed the most marked loss of suitability, considering its total area, presenting a contraction that range from 2609.18 km² to 7023.66 km² in RCPs 8.5 in 2070 and 4.5 in 2050, respectively. Based on RCP 8.5 in 2070 the Amazon urban forests suitability will decrease 7157.03 km², and 8303.98 km² in the RCP 4.5 in 2050. The Cerrado showed a loss of at least 185.58 km² (RCP 8.5 in 2070), reaching a loss of up to 2349.77 km² in RCP 8.5 in 2050. The Pampa presented between 2.31 km² and 23.21 km² of loss. The Caatinga models might diminish from 141.48 km² (RCP 4.5 in 2070) to 194.65 km² in the RCP 8.5 in 2050 scenario. The Pantanal presented few cities having more than 100,000 inhabitants; therefore, the results were also scarce. Even tough, it has been proven to have good results in modelling species for the future, even using sparse data (Dubos et al., 2022). Therefore, it is also possible to see a slight loss of suitability in some areas in the Pantanal, accounting for more than 5.9 km² in all scenarios.

4.5 Discussion

In this study, we evaluated how climate change may impact Brazilian urban forests in six different biomes. Our results suggest that, even in the more optimistic IPCC scenarios, urban forests from different biomes in Brazil are likely to be strongly affected differently by climate change, with some biomes being more vulnerable to the impacts than others. The results highlight the significant and potentially devastating impacts that climate change is expected to have on Brazilian urban forests. Here we show that the urban forests from the Atlantic Forest and the Cerrado, two biodiversity hotspots (Myers, Mittermeier, Mittermeier, da Fonseca, & Kent, 2000), are prone to be the most affected areas by future climate change, potentially losing together more than 9000 km² of the current suitable area. The impacts could extend to areas that are the most fragmented locations of Brazil and are currently home to a significant portion of the human population (Teixido et al., 2020). In Atlantic Forest and Cerrado we can find the most populated cities in the country and, as more than 68% of people will live in cities by 2050, the pressure that humanity exerts on urban forests tends to increase (UN-HABITAT, 2022). Besides the pressures employed, a larger urban population in a city without proper planning tends to increase the concentrations of greenhouse gases emissions, contributing even more to climate change (Gao et al., 2023; Xiaomin & Chuanglin, 2023). As cities expand, natural habitats such as forests, grasslands, and wetlands are often destroyed to make way for buildings, roads, and other urban infrastructure (Ellis, 2011). The findings of our study indicate that the loss of environmental suitability for urban forests is likely to occur in all regions of Brazil, regardless of the scenario considered, with the most severe impacts expected to occur in the southern and southeastern regions of the country, which highlights the need for effective and urgent action to mitigate the negative effects of climate change on Brazilian urban forests, as well as to preserve and enhance the biodiversity and ecosystem services they provide. The suitability loss can have severe consequences for the plants and animals that depend on the ecosystems for their survival and, consequently, affect the people that live in the surroundings.

Besides the possible impacts that can cause the decrease of the suitability areas of urban forests demonstrated in our results, it is interesting to mention that these studied forests might have its forest type extremely changed because of climate change or may experience another factor extremely harmful to biodiversity: a climate-induced biotic homogenization, that is, when ecosystems become more similar in terms of their species composition and structure (Hobbs et al., 2006). Although we do not studied specifically biotic homogenization in this study, this is alarming, since climate change may also play an essential role in the homogenization of woody plants in the Atlantic Forest, with loss of beta diversity in the future scenarios and a substantial expansion of generalists and disturbance-tolerant species (Zwiener, Lira-Noriega, Grady, Padial, & Vitule, 2018). And it is also worrying the trend of these changes can direct urban forests to the state of novel ecosystems, mainly due to the increase in the dominance of generalist invasive species along the process of biotic homogenization (Teixeira & Fernandes, 2019; Andrade et al., 2020; Fehr, Buitenwerf, & Svenning, 2020;). Moreover, functional homogenization is expected to happen in pessimistic scenarios concerning woody species of the Restinga vegetation along the Atlantic Forest coast (Inague, Zwiener, & Marques, 2021). This fact can disrupt the delicate balance of forest ecosystems and have negative consequences for the plants and animals that depend on these ecosystems for their survival, as well as for the ecosystem services that urban forests provide (Brockerhoff et al., 2017).

Whether it is several changes related to the decrease of environmental suitability or biotic homogenization, the results suggest that the six Brazilian biomes may face distinct negative consequences in the future, which highlights the importance of considering the specific characteristics and needs of different ecosystems when developing strategies to address the impacts of climate change (Malhi et al., 2020). This may involve developing targeted strategies that consider the unique vulnerabilities and strengths of different biomes, as well as the specific bioclimatic variables that are most important for predicting the impacts of climate change in those biomes. A nuanced understanding of the role of different climate variables in shaping the suitability of urban forests in different regions can help to inform targeted and effective management strategies that enhance the ecological functioning of plant communities in urban ecosystems and maximize the provision of ecosystem services. For example, in areas where precipitation-related variables are most important, water management strategies may be crucial for maintaining and enhancing the environmental suitability of urban forests. The strategies could include measures such as water harvesting and use of drought-tolerant tree species. In areas where temperature-related variables are most important, urban forestry management strategies may need to focus on enhancing microclimatic conditions through measures such as planting shade trees and increasing green cover (Zhang et al., 2013).

The findings of this study highlight the importance of taking action to address and mitigate the impacts of climate change on urban forests. The actions may include implementing adaptive management strategies such as diversifying tree species to increase resilience, helping areas avoid the dominance of exotic species, taking active action to support successful regeneration, facilitating the arrival of species that thrive in new climate conditions and provide benefits, realizing the inclusion of species from different functional groups in these areas, or incorporating green infrastructure solutions to reduce the negative impacts of extreme weather events (Janowiak et al., 2021; Thomas, 2020). Another contribution of the study is the general delimitation of priority areas for urban forest conservation when analyzing the differences of suitability between current and future projections. From our results, it is possible to indicate areas that need further action regarding public policies. In addition, such areas can also serve as priorities for monitoring, requiring periodic studies to verify climate impacts and act when necessary (John et al., 2020). One of the actions that may be implemented is to monitor and increase plant diversity, since diverse forests can also support a wider range of wildlife and provide a greater variety of ecosystem services. It is also important to consider the potential impacts of climate change on urban forests in the planning and design of cities. This consideration may involve designing urban green spaces that are more resilient to extreme weather events and better able to adapt to changing climate conditions.

Overall, the results of this study highlight the need for urgent action to address the impacts of climate change on Brazilian urban forests, and the importance of considering the potential impacts of climate change in urban planning and design. Given the importance of urban forests for cities in Brazil and the potential impacts of climate change on these ecosystems, urgent action must be taken to address this issue, which may include efforts to reduce greenhouse gases emissions, as well as strategies to adapt to the changes that are already underway. It will also be essential to continue researching and monitoring the impacts of climate change on urban forests in Brazil in order to better understand the risks and develop effective strategies for addressing them. Since this study used a species modelling approach to apply into urban forests occurrences it was not possible to analyze the impacts of climate change in Brazilian urban forests in a species level to more accurate conservations indications. However, the results point to a broad overview of how climate change might impact urban ecosystems in Brazil.

Our results suggest that climate change is likely to have significant and potentially harmful impacts on the environmental suitability of Brazilian urban forests, particularly in the Atlantic Forest biome. It will be important to continue monitoring and researching these impacts to understand the risks better and develop effective strategies for addressing them. In addition to studying the impacts of climate change on urban forests in Brazil, it will also be important to consider the broader context in which these forests exist, which may include factors such as urbanization, land use patterns, and availability of natural resources. Therefore, further research should focus on the impacts of other variables on the suitability of urban forests, such as land cover, soil type, soil texture, and human population density.

4.6 Conclusions

Our results suggest that climate change is likely to have significant impacts on the distribution and suitability areas of urban forests in Brazil. Overall, the results of this study highlight the importance and the need for urgent action to address these impacts to protect both human populations and biodiversity of these important environment in the cities. It will be important to continue studying the impacts of climate change on urban forests in Brazil in order to better understand the risks and to develop effective strategies for addressing them.

5. Final Considerations

In this research, we embarked on a comprehensive exploration of the intricate relationship between urban forests, ecosystem services, and the iminent threat of climate change. Of particular significance is the discernible uptick in research production post-2011, a trend that underscores the growing importance of urban ecosystems, potentially attributable to the escalating concerns about climate change impacts and urban fragility. Our extensive bibliometric review has facilitated the inspection of evolving trends, prominent sources, most productive authors, and international collaboration patterns, culminating in a panoramic understanding of the present research landscape concerning urban forests and ecosystem services. Noteworthy journals such as "Urban Forestry & Urban Greening," "Landscape and Urban Planning," and "Environmental Pollution" have emerged as key players. Terms such as "ecosystem services," "urban forest," "urban forestry," and "urban infrastructure" have emerged as focal points, underlining their recurrent prevalence and discussion in contemporary literature. The visual representation through word clouds and Sankey diagrams has provided illuminating insights into the shifting dynamics and evolving interrelationships of research themes over time, painting a vivid picture of this dynamic field. We also point out the need for more collaborations between multiple countries in articles in the area, as our results showed that these collaborations are still few.

We also delved into the complex interplay of pollutants that are sequestered and stored by urban vegetation, uncovering the multifaceted nature of this phenomenon and its dependence on various factors such as vegetation density, population size, and land use patterns. The results obtained from our analysis of the variations across different cities serve as crucial benchmarks, providing valuable insights into the development of effective strategies for enhancing urban greenery and harnessing ecosystem services to combat the ever-increasing pollution levels. Moreover, the disparities observed among cities such as Taboão da Serra and Porto Alegre shed light on the potential for targeted interventions, which can involve augmenting existing greenery or fortifying the already beneficial urban vegetation. Such interventions can lead to significant gains in terms of carbon storage and pollutant mitigation, which are critical for achieving sustainability goals.

Our last chapter casts a spotlight on the impending threats of climate change on the distribution and suitability of urban forests in Brazil. The findings of this study unequivocally underscore the critical need for proactive measures to mitigate these impacts, safeguarding the human population and the rich biodiversity that thrives within urban environments. Ongoing research on the impact of climate change on urban forests is strongly recommended in order to deepen our understanding of risks and formulate effective, targeted strategies to combat these impending challenges. Therefore, our results emphasize the urgency of addressing climate change impacts on urban forests, underscoring the necessity for coordinated efforts and evidence-based strategies to ensure the resilience and preservation of these vital urban ecosystems.

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