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Elie Hanna

The urban green infrastructure of Zaragoza (ne Spain): characteristics, regulating factors, ecosystem services and scenarios to ameliorate climate change impact

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THE URBAN GREEN INFRASTRUCTURE OF ZARAGOZA (NE SPAIN): CHARACTERISTICS, REGULATING FACTORS, ECOSYSTEM SERVICES AND SCENARIOS TO AMELIORATE CLIMATE CHANGE IMPACT

Autor

Elie Hanna

Director/es

Comín Sebastián, Francisco A.

UNIVERSIDAD DE ZARAGOZA
Escuela de Doctorado

Programa de Doctorado en Ciencias Agrarias y del Medio Natural

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THE URBAN GREEN INFRASTRUCTURE OF ZARAGOZA (NE SPAIN):

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Elie Hanna

Ph.D. Dissertation

Supervisor: Prof. Dr. Francisco A, Comín

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Escuela Politécnica Superior

Departamento de Ciencias Agrarias y del Medio Natural

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TESIS DOCTORAL

The Urban Green Infrastructure of Zaragoza (NE Spain): characteristics, regulating factors, ecosystem services and scenarios to ameliorate climate change impact

Memoria presentada por

Elie Hanna

para optar el Grado de Doctor por la Universidad de Zaragoza

Director:

Dr. D. Francisco A, Comín

Huesca, april de 2024

Escuela Politécnica Superior
Departamento de Ciencias Agrarias y del Medio Natural
Universidad de Zaragoza

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Prof. Dr. Francisco A. Comín
INSTITUTO PIRENAICO DE ECOLOGIA-CSIC
Avda Montañana 1005//Avda. Regimiento Galicia s/n
50059 **Zaragoza**.Spain//22700**Jaca**.Huesca.Spain
Ph. No..: 34-976-369393 (ext. 880058)
E-mail: comin@ipe.csic.es

El Dr. FRANCISCO A. COMÍN SEBASTIÁN, Profesor de Investigación ad honorem del Consejo Superior de Investigaciones Científicas-CSIC en el Instituto Pirenaico de Ecología,

CERTIFICA

Que la tesis doctoral titulada “The urban green infrastructure of Zaragoza: characteristics, regulating factors, ecosystem services and scenarios to ameliorate climate change impact” desarrollada por Elie Hanna en el Programa de Doctorado de Ciencias Agrarias y del Medio Natural de la Universidad de Zaragoza ha sido realizada bajo mi dirección, se ajusta al proyecto de tesis aprobado en su día, y cumple con las condiciones exigidas para optar al grado de doctor por la Universidad de Zaragoza.

Para que conste, firmo la presente en Zaragoza, a 29 de marzo 2024

Fdo.: Francisco A. Comín

REPORT ON THE PUBLICATIONS OF THE DOCTORAL THESIS

This doctoral thesis is a compendium of previously published works. It consists of four articles, published in scientific journals indexed in Web of Science (WOS) − Journal Citation Reports (JCR), one of them in the first quartile (Q1) and three in the second quartile (Q2). Elie Hanna has been the first signatory in all four publications. The complete references of the articles that constitute the body of the Doctoral Thesis are:

1. Hanna, E.; Comín, F.A. Urban Green Infrastructure and Sustainable Development: A Review. Sustainability 2021, 13, 11498 https://doi.org/10.3390/su132011498; Q2. JIF_{2022} = 3.9
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3. Hanna, E., Bruno, D. & Comín, F.A. The ecosystem services supplied by urban green infrastructure depend on their naturalness, functionality and imperviousness. Urban Ecosyst 27, 187–202 (2024). https://doi.org/10.1007/s11252-023-01442-9; Q2. JIF_{2022} = 2.9
4. Hanna, E.; Felipe-Lucia, M.R.; Comín, F.A. Scenario Analysis of Green Infrastructure to Adapt Medium-Size Cities to Climate Change: The Case of Zaragoza, Spain. Land 2024, 13, 280. https://doi.org/10.3390/land13030280; Q2. JIF_{2022} = 3.9

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ABSTRACT

The network of green spaces within urban environments, known as urban green infrastructure (UGI), has become increasingly recognized for its multiple benefits, ranging from environmental, social and economic. UGI can deliver a wide variety of ecosystem functions and services, which promote urban sustainability. However, there are still a numerous challenges regarding the evaluation of UGI effectiveness, and the assessment of their ecosystem services to support urban sustainability against the effect of climate change.

This dissertation presents an evaluation of UGI in Zaragoza, Spain, a city undergoing rapid urbanization and facing different environmental challenges. The main objective of this dissertation is to evaluate the UGI of Zaragoza and provide recommendations for enhancing the provision of ecosystem services, particularly to fight climate change. Drawing upon a literature review, different methodologies were identified to evaluate UGIs. Therefore, this research employed a different methods, qualitative and quantitative approaches to assess the effectiveness and impact of UGI sites (urban parks, university parks, agricultural lands, green walls, squares, roundabouts, forests, riparian zones, canals, cemeteries, street trees, urban forests, meanders, canals and urban natural parks) within the city of Zaragoza. The quantitative analysis encompassed fieldwork in ninety UGI sites to assess their major descriptive features and in thirty UGI sites to analyze soil and air temperature and relative humidity records to use proxy indicators of ecosystem services. Multivariate statistical analysis was employed to classify and group UGI sites, while linear and quadratic regressions were used to relate ecosystem services to UGI features and to quantify the ecosystem services provisioning of different UGI elements. GIS mapping techniques were utilized to understand their extent and distribution. As for qualitative methods, it included semi structured surveys and interviews to get the opinions and perceptions of experts, policymakers, and stakeholders.

Results from this research indicate that the number of scientific studies on UGI in relation to sustainable development has increased exponentially during the last decade and, particularly, during the last four years. However, relatively few studies have linked the study of UGI to sustainability. Most green spaces located within the city of Zaragoza have high naturalness (natural plant cover) but low functioning (footprints of ecological processes such as surface water flows, accumulated and decomposing plant material), as in many other cities. It seems that urban growth and, perhaps, the urban trend do not facilitate the establishment of green areas with a high degree of naturalness and functioning in the densely urbanized part of the cities. This study also shows that sites with high naturalness and functioning are more physiographically heterogeneous and are less regular in their shapes. Having a greater number of vegetation strata is associated with greater functioning, but increasing artificial soil reduces the functioning of green spaces. Regarding ecosystem services provisioning, this investigation has found that there is a deficit in the provision of water regulation, waste regulation, nutrient regulation, soil formation and carbon sequestration by Zaragoza's green infrastructure. Furthermore, water supply, regulation of water, soil formation, carbon sequestration and air temperature regulation are significantly and positively related to the naturalness and ecological functioning of UGI sites. A scenario analysis of the provisioning of ecosystem services by UGI in Zaragoza, to combat climate change was performed. It showed that the peri-urban areas are of high importance to stocking carbon in the soil. In the populated dense areas, the importance of urban parks and streets to act as climate refuge was highlighted, providing temperature regulation and cooling for the residents of the city.

On the basis of these findings, several implications for UGI planning, management and decision-making are drawn, which can help the city of Zaragoza and, by extension, medium-size cities to improve mitigation and adaptation to climate change: (1) Increasing the naturalness and functioning of green infrastructure (spaces with vegetation cover and the number of vegetation strata) in densely urbanized areas. This would increase the provisioning of ecosystem services and help buffer climate extremes with the consequent health benefit for citizens. (2) Diversification of UGIs and development of new green spaces where there is no enough spaces (e.g., rooftop gardens and green walls). (3) Restoration effort should not be limited to the city scale. Promoting the restoration of forests and steppes in peri urban areas, hence increasing their ecological functioning. This would help mitigate the impact of climate change through carbon sequestration. (4) Restoration efforts should focus in the city on urban parks and rivers to regulate temperature and decrease the urban heat island effect. Finally we recommend the integration of a more natural and ecologically functional green infrastructure, both in the urban and peri-urban zones, to achieve a high provision of ecosystem services and, consequently, people´s welfare.

KEYWORDS:

Urban green infrastructure, sustainable development, ecosystem services, naturalness, functioning, climate change.

RESUMEN

La red de espacios verdes dentro de entornos urbanos, conocida como infraestructura verde urbana (UGI), es cada vez más reconocida por sus múltiples beneficios, incluidos ambientales, sociales y económicos. UGI puede ofrecer una amplia variedad de funciones y servicios ecosistémicos, lo que promueve la sostenibilidad urbana. Sin embargo, todavía existen numerosos desafíos con respecto a la evaluación de la efectividad de las UGI y la evaluación de sus servicios ecosistémicos para apoyar la sostenibilidad urbana contra el efecto del cambio climático.

Esta tesis presenta una evaluación de la UGI en Zaragoza, España, una ciudad en rápida urbanización y que enfrenta diferentes desafíos ambientales. El principal objetivo de esta tesis es evaluar la UGI de Zaragoza y proporcionar recomendaciones para mejorar la prestación de servicios ecosistémicos, en particular para luchar contra el cambio climático. A partir de una revisión de la literatura, se identificaron diferentes metodologías para evaluar las UGI. En la realización de esta tesis se emplearon diferentes métodos y una combinación de enfoques cualitativos y cuantitativos para evaluar la eficacia y el impacto de los sitios de la UGI (parques urbanos, parques universitarios, terrenos agrícolas, muros verdes, plazas, rotondas, bosques, zonas ribereñas, canales, cementerios, arbolado callejero, bosques urbanos, meandros, canales y parques naturales urbanos) en la ciudad de Zaragoza. La aproximación cuantitativa abarcó trabajo de campo en noventa sitios de la UGI para evaluar sus principales características descriptivas y en treinta sitios de la UGI para analizar los registros de temperatura y humedad relativa del suelo y del aire para utilizar indicadores indirectos de los servicios ecosistémicos. Se empleó análisis estadístico multivariado para clasificar y agrupar sitios UGI, mientras que se utilizaron regresiones lineales y cuadráticas para relacionar los servicios ecosistémicos con las características UGI y para cuantificar el suministro de servicios ecosistémicos de diferentes elementos UGI. Se utilizaron técnicas de mapeo SIG para comprender su extensión y distribución. En cuanto a los métodos cualitativos, incluyeron encuestas y entrevistas semiestructuradas para obtener opiniones y percepciones de expertos, formuladores de políticas y grupos de interés.

Los resultados de esta investigación indican que el número de estudios científicos sobre UGI ha aumentado exponencialmente durante la última década y, particularmente, durante los últimos cuatro años, pero relativamente pocos se han relacionado con el desarrollo sostenible. La mayoría de espacios verdes ubicados dentro de la ciudad de Zaragoza presentan una alta naturalidad (cobertura por vegetación natural) pero una baja funcionalidad ecológica (signos de procesos ecológicos como flujos de agua superficial, acumulación y descomposición de materia vegetal), como ocurre en muchas otras ciudades. Parece que el crecimiento urbano y la tendencia urbanística no facilitan el establecimiento de zonas verdes con un alto grado de naturalidad y funcionalidad en la parte densamente urbanizada de las ciudades. Este estudio también muestra que los sitios con alta naturalidad y funcionalidad son más heterogéneos fisiográficamente y menos regulares en sus formas. Tener un mayor número de estratos de vegetación se asocia a una mayor funcionalidad ecológica, pero aumentar el suelo artificial reduce la funcionalidad de los espacios verdes. En cuanto a la prestación de servicios ecosistémicos, esta investigación ha demostrado que existe un déficit en la provisión de regulación hídrica, regulación de residuos, regulación de nutrientes, formación de suelo y secuestro de carbono por parte de la infraestructura verde de Zaragoza. Además, el suministro de agua, la regulación del agua, la formación del suelo, el secuestro de carbono y la regulación de la temperatura del aire están significativa y positivamente relacionados con la naturalidad y

el funcionamiento ecológico de los sitios UGI. Se realizó un análisis de escenarios de prestación de servicios ecosistémicos por parte de la UGI en Zaragoza, para combatir el cambio climático. Y se demostró que las áreas periurbanas son de gran importancia para almacenar carbono en el suelo. En las zonas densamente pobladas, destaca la importancia de los parques y calles urbanas para actuar como refugio climático, proporcionando regulación de temperatura y enfriamiento a los residentes de la ciudad.

A partir de estos hallazgos se extraen varias implicaciones para la planificación, gestión y toma de decisiones de la UGI, que pueden ayudar a la ciudad de Zaragoza a mejorar la mitigación y adaptación al cambio climático: (1) Incrementar la naturalidad y funcionamiento de las infraestructuras verdes (espacios con la cobertura vegetal y el número de estratos vegetales) en zonas densamente urbanizadas. Esto aumentaría la prestación de servicios ecosistémicos y ayudaría a amortiguar los extremos climáticos con el consiguiente beneficio para la salud de los ciudadanos. (2) Diversificación de las UGI y desarrollo de nuevos espacios verdes donde no hay suficientes espacios (por ejemplo, jardines en las azoteas y muros verdes). (3) Los esfuerzos de restauración no deben limitarse a la escala de la ciudad. Promover la restauración de bosques y estepas en zonas periurbanas, aumentando así su funcionamiento ecológico. Esto ayudaría a mitigar el impacto del cambio climático mediante el secuestro de carbono. (4) Los esfuerzos de restauración de la ciudad deberían centrarse en parques urbanos y ríos para regular la temperatura y disminuir el efecto de isla de calor urbana. Finalmente, recomendamos la integración de una infraestructura con más naturalidad y, sobre todo, funcionalidad ecológica, tanto en la zona más urbana como en la peri-urbana del municipio, para conseguir una alta provisión de servicios ecosistémicos y, consecuentemente, bienestar para la población.

PALABRAS CLAVE:

Infraestructura verde urbana, desarrollo sostenible, servicios ecosistémicos, naturalidad, funcionalidad, cambio climático.

TABLE OF CONTENTS

1. INTRODUCTION 1
1.1 Context 1
1.2 Green Infrastructure 1
1.2.1 Emergence of Green Infrastructure: A Historical Perspective 1
1.2.2 Understanding the Definitions of Green Infrastructure 4
1.3 Urban Green Infrastructure 6
1.3.1 Difference between Green Infrastructure and Urban Green infrastructure 6
1.3.2 Elements of Urban Green Infrastructure 6
1.3.3 Urban Green Infrastructure: its relevance in advanced XXI century 7
1.3.4 Sustainable Development Goals 9
1.3.5 Ecosystem Services Provisioning 11
1.3.6 Addressing the Challenges of Climate Change 13
1.3.7 Restoring Urban Green Infrastructure 14
1.4 Objectives of the Doctoral Thesis 15
1.4.1 Hypothesis 15
1.4.2 General Objective 15
1.4.3 Specific Objectives 15
1.5 Study Area 15
1.6 Justification of the Thematic Unity of the Articles 17
1.7 General Methodology 17
2. COMPENDIUM OF PUBLICATIONS 19
3. GENERAL DISCUSSION 90
3.1 Updates and Advancements: 2020-2024 in Review 90
3.2 Conceptual and Methodological Contributions 94
3.3 Research Limitations 95
3.4 Implications for planning and decision-making 96
4. CONCLUSIONS 99
APPENDIX 104
REFERENCES 105

LIST OF TABLES

Table 1: Different terms of green infrastructure and their definitions. Source: https://www.policyinnovation.org/blog/navigating-the-terms-gi-nbs (adjusted) accessed on 29/02/2024

Table 2: Urban green infrastructure initiatives in different cities worldwide.

Table 3: Citation report of the 10 most cited articles between the 505 articles reviewed.

LIST OF FIGURES

Figure 1: Ancient agora in Athens/Greece. Source: https://www.atlasobscura.com/places/the-athenian-agora-athens-greece accessed on 10/03/2024

Figure 2: The Courtyard of Santa Isabel in the Aljafería Palace. Source: https://www.turismodearagon.com/ficha/palacio-de-la-aljaferia-zaragoza/ accessed on 11/03/2024

Figure 3: Study area corresponding to the municipality of Zaragoza (Spain). This map shows the population density of the city.

Figure 4. Diagram illustrating the different chapters of this study

Figure 5: Keywords most frequently used in the articles reviewed between 2020-2024. Bigger circles correspond to the most used keywords.

Figure 6: Number of publications per country. Source: Web of Science (adjusted)

Figure 7: Publications per population comparison

Figure 8: Correspondences between the documents obtained in this review and SDGs. It is important to note that some article may correspond to more than one SDGs goal. Source: Web of Science (adjusted)

ABBREVIATIONS

UGI: Urban Green Infrastructure

GI: Green Infrastructure

ES: Ecosystem Services

SD: Sustainable Development

SDG: Sustainable Development Goal

Nat: Naturalness

Fun: Functioning

1. INTRODUCTION

1.1 Context

Population has witnessed rapid growth recently leading, together a series of major drivers [1], to extensive urban sprawl and the expansion of cities worldwide [2]. Especially in urban zones with a mid to high number of inhabitants, where the urbanized areas are facing constant transformation. Therefore, applying the sustainable development principles is a must for cities. The latter are showing dynamic change in spatial distributions over time. However, a common challenge faced by many urban areas is to balance this rapid urbanization that is accompanied by an increase of pollution, and many cities are lacking proper planning for green infrastructure, which are essential for promoting environmental and overall well-being.

In recent years, a growing number of scholars have begun to examine scientific approaches that promote sustainable development in urban zones [3]. Furthermore, many nations and regions have included green infrastructure into their urban and regional sustainable development programs and policies as people start to realize how important it is for sustainable development.

In the next sections of this Introduction, a review of previous knowledge which inspired and on which is based this thesis is presented.

1.2 Green Infrastructure

1.2.1 Emergence of Green Infrastructure: A Historical Perspective

Green infrastructure has been an integral part of human settlements since the Neolithic period [4]. While the term "green infrastructure" might be relatively modern [5], the principles behind it have been practiced in various forms throughout history. We can say that the history of green infrastructure elements and the history of gardens are interrelated, and coincided.

Between the 8th Century BC –and the first Century BC. Greece adopted the concept of green Infrastructure with the invention of Greek *agora*. Agoras were meeting spaces that were designed as gathering places for social interactions. Many of these were constructed all around Greece, and some of them included natural elements into the architecture, creating public spaces for nature [6].

Fig. 1. Ancient agora in Athens/Greece. Source: https://www.atlasobscura.com/places/the-athenian-agora-athens-greece accessed on 10/03/2024

The Romans took roof gardening to another level; they planted trees on institutional buildings and even imported some of them, which was a massive undertaking. These gardens functioned as a conceptual, sensual and physical space in Roman society, and their use as a vehicle of cultural communication [7].

In the north of Spain, and particularly in Zaragoza, the Aljafería Palace was built during the second half of the 11th century in the Taifa of Zaragoza in Al-Andalus, present day Zaragoza, Aragon, Spain. The structure is one of the few conserved large example of Spanish Islamic architecture from the era of the taifas (independent kingdoms). The Courtyard of Santa Isabel is an open, landscaped space that unified the whole palace. It is characterized by its Moorish style, resembling the Alhambra gardens. It contains a marble floor, a small water canal that divides the courtyard into two, and a small pool in the south that has been conserved. As we will explain later, the canals and waterways are a valuable part of a green infrastructure network. They also provide an important wildlife route and act as stepping stones for mitigation against habitat loss, dispersal and the genetic exchange of plants [8].

Fig. 2. The Courtyard of Santa Isabel in the Aljafería Palace. Source: https://www.turismodearagon.com/ficha/palacio-de-la-aljaferia-zaragoza/ accessed on 11/03/2024

In Southern Europe steeply terraced gardens, green facades, and green roofs were common during the middle Ages and the Renaissance. However, the access to the green infrastructure elements was only given to the rich, which showed a discrepancy that still remain issue today especially as low-income areas have lower access to green spaces and are exposed to higher levels of pollutants and poor sound environments [9-11].

In France, in the 17th century, the inequality was in its peaks [12]. Living conditions in the cities were bad, which led the rich and the wealthy to create lush gardens and promenades that would separate the French aristocracy from the commoners.

In USA, in the 19th century, the environmental movement gained momentum in the 19th century with many novel thoughts around conservation and the human need for access to greenery [13]. Henry David Thoreau, American philosopher, poet, and environmental scientist, said, "I think every town should have a park." This eventually led to incredible developments in the US related to parks and urban planning.

As we saw, historically, the concepts of green infrastructure were utilized far earlier than today. However, the term "green infrastructure" did not emerge until the early 1990s, in a 1994 report to Florida Governor Lawton Chiles by Buddy MacKay, chair of the Florida Greenways Commission, regarding the Florida Greenways Project, a green infrastructure project started in 1991. MacKay stated, "Just as we carefully plan the infrastructure our communities need to support the people who live there—the roads, water and electricity—so must we begin to plan and manage Florida's green infrastructure". This plan outlined the vision for the state's Greenways and Trails System, both on land and water. It defines the role of the

system in advancing Florida's economy, tourism, public health, transportation choices, recreation, conservation and quality of life [14].

At this point, it is important to remark the perspective of this thesis. It focused on urban green infrastructure. However, cities are not independent units of the ecological area. Neither as ecosystems nor as social systems. Urban zones are separated from rural or natural areas. Cities are based on the raw materials (cement, water, energy, food) produced in rural areas and receive permanently or temporally persons born or grew up in rural areas. So, this perspective should be also take into account in the study of socio-ecological systems as cities or urban zones. For the purpose of this thesis the study of urban green infrastructure is considered.

1.2.2 Understanding the Definitions of Green Infrastructure

Many definitions have emerged describing the green infrastructure. The European Commission (2010) defined it as "A strategically planned network of natural and semi-natural areas with other environmental features, designed and managed to deliver a wide range of ecosystem services, while also enhancing biodiversity". Examples of these services are the purification of water, the enhancement of air quality, the provision of recreational space, and assistance with climate adaptation and mitigation. This network of green (land) and blue (water) spaces enhances the environment's quality, the state and connectedness of natural regions, and the general well-being of the populace. The European Commission considers Green Infrastructure as a proven tool that provides ecological, economic and social benefits through natural solutions and that helps us understand the value of the benefits that nature provides to human society and mobilize investments to sustain and strengthen them [15].

Building green infrastructure may boost the green economy and provide employment [16]. The Conservation Fund and the Department of Agriculture of the United States (USDA) Forest Service, in 1999, have jointly defined the terminology 'green infrastructure' as "green infrastructure is our nation's natural life support system, is an interconnected network of waterways, wetlands, woodlands, wildlife habitats, and other natural areas; greenways, parks and other conservation lands; working farms, ranches and forests; and wilderness and other open spaces that support native species, maintain natural ecological processes, sustain air and water resources and contribute to the health and quality of life for America's communities and people" (Benedict & McMahon, 2000). In 2019, The American Congress enacted the Water Infrastructure Improvement Act, which defines green infrastructure as "the range of measures that use plant or soil systems, permeable pavement or other permeable surfaces or substrates, stormwater harvest and reuse, or landscaping to store, infiltrate, or evapotranspirate stormwater and reduce flows to sewer systems or to surface waters."

However, a confusion exists between the two terms, green infrastructure and green spaces. According to Forest Research (2010), which is the research agency of the Forestry Commission and Great Britain's principal organization for forestry and tree-related research, green infrastructure refers to the network of different types of green spaces which together enable delivery of multiple benefits as goods and services. Green spaces are any vegetated areas of land or water within or adjoining an urban area. Additionally, green infrastructure also includes some aspects of the marine and water environment – or 'blue infrastructure' – such as rivers, wetland and meanders. The latter highlights an importance difference between the two terms. However, some researchers still uses the two as synonyms, especially as we will see later,

that green infrastructure is consisted of different elements, which if we exclude the aquatic ones, could be the synonym of different types of green spaces, especially in urban areas.

Another term that draws confusion, is nature based solutions (NbS). Nature can make important contributions to climate protection and adaptation to climate change, through "nature-based solutions" (NbS) as part of green infrastructure. The preservation of peatlands and species-rich permanent grasslands as significant CO_2 storage, the renaturation of floodplains as retention areas to lessen flood peaks, and the use of urban green spaces to mitigate heavy rainfall episodes in urban areas are a few examples of NbS to climate protection and adaptation. Moreover, NbS can aid in wastewater purification, soil decontamination, and land recycling. Furthermore, these natural remedies have many more advantages than conventional ones, are economical, and frequently result in lower long-term costs. As a result, natural solutions might be viewed as an all-encompassing substitute for or addition to strictly technical ones [17].

Table 1: Different terms of green infrastructure and their definitions. Source: https://www.policyinnovation.org/blog/navigating-the-terms-gi-nbs (adjusted) accessed on 29/02/2024

Term	Definitions
Green infrastructure (GI)	The network of different types of green spaces which together enable delivery of multiple benefits as goods and services. Green spaces are any vegetated areas of land or water within or adjoining an urban area
Nature-based solutions (NbS or NBS)	"Actions to protect, sustainably manage, or restore natural or modified ecosystems to address societal challenges, simultaneously providing benefits for people and the environment" (the Roadmap); most often used in a climate change context and at the international level
Blue-Green Infrastructure	Similar to green infrastructure, but includes emphasis on "blue" elements, such as rivers, canals, and ponds. Since these elements are inextricably intertwined with natural elements, there isn't much need to parse them out.
Ecological infrastructure	A synonym for green infrastructure; stems from an ecosystem services line of thought; refers to any part of nature that provides benefits to an urban area.
Engineering with nature	A synonym for nature-based solutions; the use of natural systems to deliver economic, environmental, and social benefits; spearheaded by the US Army Corps of Engineers.
Green Stormwater Infrastructure (GSI)	A synonym or subset of green infrastructure with a stronger focus on stormwater management.
Low-impact development (LID)	A synonym for green infrastructure; also has a strong focus on stormwater management.
Natural climate solutions (NCS)	A synonym or subset of nature-based solutions; focused on climate mitigation; refers to conservation, restoration, or other land management that increase carbon storage or decrease greenhouse gas emissions; can include forests, saltmarshes, seabeds.

Natural infrastructure	First used to highlight the significance of wetlands and more natural, less engineered landscapes, like coastlines or wetlands, but still includes an active management component.
Stormwater best management practices (BMP)	Often used as a synonym for green infrastructure; includes actions that reduce pollution in stormwater runoff in urban, residential, and agricultural areas. These actions include green infrastructure, but do not necessarily need to utilize natural elements–an example is silt fencing.
Stormwater control measures (SCM)	Similar to stormwater best management practices, see above.
Sustainable urban drainage systems (SuDS or SUDS)	Synonym for green infrastructure; refers to a more natural approach to managing stormwater.

1.3 Urban Green Infrastructure

1.3.1 Difference between Green Infrastructure and Urban Green infrastructure

While green infrastructure is a broader term that encompasses all types of natural and semi-natural elements, including those in both urban and non-urban areas. Urban green infrastructure (UGI) refers to a network of green spaces, water and other natural features within urban areas (The UK Houses of Parliament, 2013). Urban green infrastructure includes different types of blue-green elements such as forests, wetlands, agricultural land, public parks, private gardens, single green elements (street trees, green roofs, etc.) and ponds, canals and streams. These play a crucial role in enhancing climate adaptation and mitigation capacities, and reducing negative impacts of climate change hazards such as heat waves, flooding and drought in cities. We can also deduct that the "elements of urban green infrastructure" could be synonymous with the term of "types of urban green spaces" as accepted in a broad sense.

1.3.2 Elements of Urban Green Infrastructure

In their study, Cvejic, R. et al. (2015) [18], proposed a typology for urban green spaces, which inspired the author of this document to adopt it, and adapt it to the case study chosen for his thesis.

The different types are:

- Urban parks: Mainly located in the populated zones in cities, used mainly for their environmental, aesthetical and recreational benefits [19].
- Urban forests: Play an important role in ecology of human habitats in many ways. Aside from the beautification of the urban environment, they offer many benefits like impacting climate and the economy while providing shelter to wildlife and recreational area for city dwellers [20].
- Cemeteries: Highly vegetated cemeteries can provide important public green spaces in urban environments and give recreational opportunities to city residents [21].
- Roundabouts: Considered as an integral part of broader landscape systems, and therefore as an opportunity to connect different elements of UGI [22].
- Urban natural parks: These are urban parks but with the difference that less artificial intervention was notices. Also, the preservation of the hydro-geomorphological aspects is noticed in these sites [23].

- Squares or Plazas (in Spanish): If well-designed, could play an important role in UGI, and be beneficial for the abundance of biodiversity, while preserving its cultural and recreational benefits [24].
- Street trees: Urban areas often experience high temperatures due to the urban heat island effect. Street trees can help combat this problem by providing shade and decreasing building energy use [25].
- Green walls and roofs: Can mitigate air pollution levels by lowering extreme summer temperatures through photosynthesis and capturing gases. They can dramatically transform the surrounding environment and create a striking visual impact [26].
- Meander: Part of the blue-green infrastructure, located in the suburban and peri urban areas, are part of the UGI, due to their fundamental characteristic of flowing water and is critical to the physical stability of the channel and the health of the rivers [27].
- Rivers: Part of the blue-green infrastructure, located in the city and in the suburban and peri urban areas. Their riparian areas are of high importance, because riparian vegetation can remove excess nutrients and sediment from surface runoff, stabilizing stream banks and reducing floodwater velocity [28].
- Forests: Like urban forests, they are importance due to the abundance of trees, which can helps in sequestering large amounts of Carbons into the soil, hence reducing the pollution in the city. They are located in the sub and peri urban area [29].
- University parks: They provide recreational, environmental, educational and aesthetical services that help students enjoy their breaks in the middle of nature [30].
- Community garden: They can reduce urban heat islands, provide various ecosystem services, and increase storm water retention. From a socio-economic perspective, these gardens also build trust, facilitate participation, improve responses to natural disasters and food security – all vital components of effective adaptation and resilience to climate change [31].
- Canal: Part of the blue-green infrastructure. They can reconnect disparate habitats, and provide biodiversity and improvements for wildlife [32].
- Agricultural lands: Located in the sub and peri urban areas. They could be importance of storing carbon and fixing it in the soil. They can also provide connectivity between the urban and the rural [33].

1.3.3 Urban Green Infrastructure: its relevance in advanced XXI century

The degradation of environmental and social life in urban zones aroused the interest for sustainability through UGI development and improvement. The interest in UGI has grown globally (Table 2), with significant attention given to its application in Europe, the USA, China, and various other regions [34]. Public and private investment in green urban infrastructure such as parks, forests and roof gardens is expected to increase from US$606 billion globally in 2022 to US$978 billion in 2030, (according to ABI Research, 2022, https://www.abiresearch.com/press/ accessed on 03/03/2024). Increased number of papers, reports, directives, had encompassed a wide array of topics relative to UGI planning [35]. These include investigations into the spatial distribution of green spaces, strategies for enhancing connectivity between them [36], analysis of their structural characteristics [37], assessments of biodiversity within urban environments [38], examinations of the ecosystem services they provide [39], and evaluations of the social benefits they offer to communities [40]. Understanding the importance of UGI is crucial in achieving sustainable development goals in cities, addressing challenges related to

climate change, and enhancing overall urban resilience. This recognition highlights the critical role that UGI plays in providing ecosystem services essential for the well-being of urban environments and their inhabitants.

Table 2: Urban green infrastructure initiatives in different cities worldwide.

City	Initiatives	Sustainable practices
New York City	High Line Park	The plant selection favors native, drought-tolerant, and low-maintenance species, cutting down on the resources that go into the landscape. The ecosystem also provides food and shelter for wildlife species, including native pollinators.
	Brooklyn Bridge Park	Salvaging materials, sound attenuation, conserving energy, recycling stormwater, growing organically, greening roofs, supporting butterflies communities, recreation habitats and restoring oysters, are a group of sustainable environmentally responsible practices that were implemented in the Brooklyn Bridge Park
	Million Trees NYC initiative	Initiative to make New York city sustainable by 2030, includes planting street trees in all possible locations, creating 400 new "Greenstreets" and reforesting 2,000 acres of parkland. Therefore, balancing green space with urban development through green infrastructure
Tokyo	Yoyogi Park	Provide a balance between the environment and the social, it is an eco-friendly park that's making waves on the ecotourism circuit.
London	Hyde Park	The trees in Hyde Park provides benefits that include carbon sequestration, stormwater attenuation, and air pollutant removal.
	Queen Elizabeth Olympic Park	Building sustainable neighborhoods and communities, creating biodiverse parks and waterways, managing parks and waterways for the benefit of wildlife and people, ensuring the Park works to limit and adapt to climate change, are all examples of sustainable goals have been worked on in the park.
Singapore	Gardens by the Bay	Minimizing solar heat gain, cooling only the occupied zones, generating energy and harnessing waste heat, filtering of water run-off, reducing nutrient load, planting a carbon sink, providing opportunities for wildlife encounters. All examples of environmentally friendly methods have been worked on in the park

Singapore	Bukit Timah Nature Reserve	It is recorded as having 1000 species of flowering plants, 10,000 species of beetles, and many other organisms and does retain an authentic 'feel' of a primeval rainforest in the interiors [41].

1.3.4 Sustainable Development Goals

In September 2015, the 2030 Agenda for Sustainable Development, was adopted by all United Nations Member States in United Nations Headquarters in New York. The Sustainable Development Goals replaced the Millennium Development Goals (MDGs), which in September 2000 rallied the world around a common 15-year agenda to tackle the indignity of poverty. The agenda is composed of 17 Sustainable Development Goals (SDGs), and 169 targets, which are an urgent call for action and global partnership between developed and developing countries. UGI can play an important role in achieving several of these goals. These goals covered a broad range of important issues, including poverty eradication, quality education, gender equality, clean water and sanitation, affordable and clean energy, climate action, and sustainable cities and communities, and others. The SDGs have the goal to focus the efforts on combating inequality, eradicating all forms of poverty, and addressing climate change by 2030.

The 17 Sustainable Development Goals (SDGs) are:

SDG1: No poverty; the goal is to end poverty in all its forms everywhere and that all people have access to basic necessities such as food, shelter, and healthcare. UGI can contribute to poverty eradication by creating job opportunities through the construction and maintenance of green spaces, such as parks and community gardens, thus providing income for individuals and families in urban zones [42].

SDG2: Zero Hunger; it aims to end hunger, achieve food security and improved nutrition, and promote sustainable agriculture. Community gardens (an urban green infrastructure element), can promote sustainable agriculture practices and can contribute to local food production, improving access to nutritious food and addressing food insecurity in urban areas [43].

SDG3: Good Health and Well-being; by promoting well-being for all ages. Its objective is to provide access to healthcare services, reduce maternal and child mortality, and combat diseases such as HIV/AIDS, malaria, and tuberculosis. Access to urban green spaces has been linked to improved physical and mental health outcomes, providing opportunities for exercise, relaxation, and stress reduction [44].

SDG4: Quality Education; it aims to ensure inclusive and equitable quality education and promote lifelong learning opportunities for all. It focuses on providing universal access to education, improving the quality of education, and promoting learning opportunities for people of all ages. Urban green spaces such as botanical gardens and nature reserves, serve as outdoor classrooms, providing opportunities for experiential learning and environmental education [45].

SDG5: Gender Equality; by achieving gender equality and empowering all women. This SDG aim to eliminate discrimination and violence against women and girls, provide equal access to education and economic opportunities, and promote women's participation in

decision-making processes. UGI sites such as urban parks, can prioritize inclusivity and accessibility, ensuring that women feel safe, have equal access and participation in green spaces, especially in developing countries, thereby promoting gender equality in their cities [46].

SDG6: Clean Water and Sanitation; by ensuring availability and sustainable management of water and sanitation for all. This SDG focuses on providing access to clean drinking water, improving sanitation facilities, and promoting water conservation and sustainable water management practices. UGI can help manage stormwater runoff, reduce pollution, and deliver clean water supply, contributing to improved water quality and sustainable water management [47].

SDG7: Affordable and Clean Energy; the goal is to ensure access to affordable, reliable, sustainable, and modern energy for all. This goal aims to promote the use of renewable energy sources, increase energy efficiency, and expand access to electricity in developing countries. The presence of urban green spaces such as urban parks, green roofs and green walls, can contribute to energy efficiency and conservation efforts by acting as cooling refuges, hence providing natural cooling and reducing the urban heat island effect [48].

SDG8: Decent Work and Economic Growth; by promoting sustainable economic growth, full and productive employment, and work for all. This SDG focuses on creating jobs, encouraging entrepreneurship, and promoting economic development. The concept of green infrastructure has emerged internationally as a way to promote economic growth and development using natural or man-made assets to provide resources and environmental services [49].

SDG9: Industry, Innovation, and Infrastructure; it aims to build resilient infrastructure, promote sustainable industrialization, and encourage innovation, especially in developing countries. UGI projects can incorporate innovative technologies and sustainable design principles to build resilient and eco-friendly infrastructure. Permeable pavement is an example of innovation in the field of sustainable drainage systems [50].

SDG10: Reduced Inequalities; by reducing inequality within and among countries. This SDG focuses on reducing income inequality, promoting social inclusion, and ensuring equal opportunities for all, regardless of gender, race, or socioeconomic status. Access to urban parks for example, can promote equality, providing recreational and communal spaces where people from diverse backgrounds can interact and connect [51].

SDG11: Sustainable Cities and Communities; by making cities and human settlements inclusive, safe, resilient, and sustainable. This SDG has an objective to promote sustainability in cities, improve access to basic services, and enhance urban resilience to disasters and climate change. UGI plays an important role in creating sustainable cities by enhancing urban biodiversity, improving air and water quality, and promoting community health and well-being [52].

SDG12: Responsible Consumption and Production; by ensuring sustainable consumption and production patterns. This SDG focuses on promoting resource efficiency, reducing waste and pollution, and encouraging sustainable consumption and production practices. UGI can provide opportunities for recycling, composting, and waste reduction [53].

SDG13: Climate Action; by taking urgent action to combat climate change and its impacts. This SDG aims to strengthen resilience and adaptive capacity to climate-related hazards and natural disasters, and to integrate climate change measures into national policies, strategies, and planning. UGI helps mitigate the impacts of climate change by sequestering carbon, reducing urban heat island effects, and enhancing climate resilience [54].

SDG14: Life Below Water; by the conservation and sustainable use of the oceans, seas, and marine resources for sustainable development. It focuses on protecting marine ecosystems, reducing marine pollution, and promoting sustainable fisheries management. Urban green infrastructure including blue infrastructure such as wetlands, canals, rivers and its riparian areas, can contribute to the conservation of aquatic ecosystems and marine resources [55].

SDG15: Life on Land; by protecting, restoring, and promoting the sustainable use of terrestrial ecosystems, and sustainable management of forests, also combating desertification, and halting and reversing land degradation and stopping biodiversity loss. UGI projects can help preserve green spaces, conserve biodiversity, and mitigate habitat loss and fragmentation in urban environments [56].

SDG16: Peace, Justice, and Strong Institutions; by promoting peaceful societies, providing access to justice for all, and building effective, accountable institutions at all levels. This SDG focuses on promoting rule of law, providing access to justice, and building effective and accountable institutions. Mosaic governance aims for a context-sensitive way of UGI planning, enhancing relationships between the diversity of landscapes and communities across cities. Hence promoting community engagement and civic participation, contributing to the promotion of peaceful societies [57].

SDG17: Partnerships for the Goals; a successful sustainable development agenda requires partnerships between governments, the private sector and civil society. These partnerships built upon principles and values, a shared vision, and shared goals that place people and the planet at the center, are needed at the global, regional, national and local level. The same can be said for UGI projects, where collaboration in different ways between the public and private sectors, and the communities is needed, at different scales, local, and national, in order to achieve the SDGs in cities [58].

In Europe, the European Union (EU) made a positive and constructive contribution to the development of the 2030 Agenda. Europe is taking the fight against climate change seriously. For instance, Denmark tops the Climate Change Performance Index for the third year in a row in 2024. The Nordic nation scores “high” in the greenhouse gas emissions and renewable energy categories. Protecting the environment and taking care of it is a priority for Europe, with commitments to address climate change, pollution, and biodiversity loss. These issues are closely linked to several SDGs, including SDG11 (Sustainable Cities and Communities), SDG13 (climate action), and SDG14 (life below water) and SDG15 (life on land).

1.3.5 Ecosystem Services Provisioning

“Ecosystem services” (ES) are defined as the ecological characteristics, functions, or processes that directly or indirectly contribute to human well-being – the benefits people derive from functioning ecosystems [59]. However, ecosystem processes and functions may contribute to ecosystem services but they are not synonymous. Ecosystem processes and functions describe biophysical relationships and exist regardless of whether or not humans benefit [60]. For

instance, wetland can act as natural filter, and therefore, one ecosystem function of wetlands is water filtration, and the ecosystem service produced by this ecosystem function is water purification, by removing pollutants and excess nutrients from water, improving water quality for drinking and agriculture, which provide direct benefits for human health and socio-economic development.

Urban Green Infrastructure provides a diverse array of ecosystem services [61]. Four main kinds of ecosystem services were identified by the Millennium Ecosystem Assessment (MA) [62], a significant UN-sponsored initiative to examine how human activity Four main kinds of ecosystem services were identified by the Millennium Ecosystem Assessment (MA) affects ecosystems and human well-being: providing, regulatory, cultural, and sustaining services.

1. Provisioning Services: Anything that benefits humans and may be obtained from nature is considered a provisioning service. Provisioning services of UGI, encompass food production through community gardens and urban agriculture [63]. Another important provisioning service is water supply, which can be used for different purposes (e.g., irrigation, drinking water) [64].
2. Regulating Services: A regulating service is the benefit provided by ecosystem processes that moderate natural phenomena. UGI provide various regulating services in the urban environment. Climate regulation is one of these services through mitigating the urban heat island effect, reducing temperatures, and improving air quality [65]. Also, water regulation through storm water management and reducing flooding, as well as reducing pollutants and improving the water quality [64]. Furthermore, regulating services include pollination, decomposition, water purification, erosion and carbon storage [66].
3. Supporting Services: UGI supports the functioning of ecosystems. Ecosystems themselves could not be sustained without the consistency of underlying natural processes, such as photosynthesis, soil formation, biodiversity enhancing and nutrient cycling [67].
4. Cultural Services: Non-material benefits that UGI provides to society, that contributes to the development and cultural advancement of people, including how ecosystems play a role in local, national, and global cultures, the building of knowledge, enhancing creativity from interactions with nature, and recreation [68].

A more detailed classification of ecosystem services was established by Haines-Young, R. (2023) [69].

Assessing ecosystem services in UGI is essential for understanding the multiple benefits that these green spaces provide to the residents in urban areas. It involves identifying, quantifying, and valuing these services, also understanding the different interactions, i.e. trade-offs and synergies between the different types of ecosystem services, in order to inform planning, design, and management decisions. Different methodologies and several approaches are used in ecosystem services assessment in green infrastructure, each offering unique insights into the benefits that these spaces provide to cities, we list the most common ones:

- Direct measurements and ecosystem services quantification: It involve direct measurements and observations of ecological processes and functions in the UGI

element. This approach may include plant sampling, soil sampling, and using data loggers to measure vegetation cover, species diversity, and habitat quality, as well as monitoring of soil quality, water quality, air pollution, and microclimate conditions such as temperature and humidity [70].

- Remote sensing and Geographic Information Systems (GIS): Remote sensing techniques, such as satellite imagery and aerial photography, coupled with GIS technology (for example ArcGIS), are important tools for mapping and analyzing UGI and its ecosystem services. Remote sensing can be used to assess the extent and distribution of green spaces, vegetation cover, urban heat island effect and land use patterns in urban areas [71]. GIS allows for spatial analysis of ecosystem services, such as estimating carbon sequestration and temperature regulation provided by UGI sites.
- Artificial Intelligence and Machine Learning: Artificial intelligence is increasingly being used to assess ecosystem services, changing the way we understand, quantify, and know the benefits that ecosystems provide to society. Artificial intelligence methods, such as machine learning, remote sensing, and big data analytics, offer powerful tools for analyzing large and complex datasets, identifying patterns, and making predictions about ecosystem dynamics and the provision of ecosystem services. Two examples are open source software; InVEST (Integrated Valuation of Ecosystem Services and Trade-offs), developed by the Natural Capital Project. InVEST enables users to map and quantify the benefits provided by ecosystems, such as carbon storage, water purification, and habitat provision. Also, ARIES (Artificial Intelligence for Ecosystem Services), a software platform developed by the University of Vermont's Gund Institute for Environment that uses artificial intelligence to model and map ecosystem services [72].
- Economic valuation: Economic valuation methods are used to quantify the monetary value of ecosystem services provided by urban green infrastructure. They employ a cost-benefit analysis, in order to know the return on investment of UGI. They also could measure the economic benefits such as property values, avoided costs of air and water pollution and the job opportunities created by UGI sites [73].
- Social assessments: They focus on understanding the non-material benefits and values associated with UGI. They involve conducting surveys, interviews, and workshops with local residents, experts and stakeholders in order to understand their perceptions, preferences, and attitudes towards UGI. These evaluations provide information about the cultural ecosystem services such as recreational, aesthetic, and educational benefits of UGI, as well as their role in promoting community engagement, social cohesion, and cultural identity in urban neighborhoods [74].

As we examined the complexities of UGI ecosystem services, it became more and more clear how these mechanisms not only promote urban sustainability, but also play a critical role in mitigating the effects of climate change.

1.3.6 Addressing the Challenges of Climate Change

The global increase in temperature leads to higher ocean levels, frequent extreme weather events like floods, droughts, and storms, as well as the expansion of tropical diseases [75]. These factors collectively have significant repercussions on essential urban services and infrastructure

[76]. UGI offers benefits that are crucial for adapting to climate change, notably in reducing the urban heat island and providing cooling shelters [77]. Also UGI contributes to sequestering carbon into the soil with the aim of mitigating the impact of greenhouse gases on climate change by decreasing their accumulation in the atmosphere [78]. Effectively addressing this impact is through implementing and restoring various UGI elements in urban areas, such as urban parks, urban forests, green rooftops, forests, squares, roundabouts and other green spaces, which can help to mitigate climate effects [77].

In order to control excessive rainfall and sea level rise, cities could also use green infrastructure solutions [79]. For instance, Curitiba, Brazil, uses green spaces, and permeable pavement to control rainfall. Native vegetation, in wetlands may be used by coastal towns to retain water, strengthen shorelines, and lessen storm surges [80]. Mangroves, for example, may lessen storm surges by up to 55 cm and wave heights by up to 66%, which might help save over 18 million people and $82 billion in assets [81]. When it comes to damage avoided, green infrastructure may have a significant positive impact. Existing wetlands are estimated to have saved $625 million in property damage during Hurricane Sandy in the United States [82].

1.3.7 Restoring Urban Green Infrastructure

This thesis focusses on the characterization and evaluation of Zaragoza UGI and providing suggestions for its restoration in order to adapt Zaragoza to climate change. These are preliminary steps of a strategy to implement the restoration of UGIs. Other aspects are required to construct such strategy: connectivity of the sites conforming the UGI, social perception and participation for the definition of objectives, economic valuation of restoration actions, between others. In this thesis, we can´t study these interesting factors because of the limitations to develop a Ph. D. thesis. However, presenting a few points of interest will give a better perspective of our idea with respect to the restoration of UGIs.

The restoration of UGI must consider the space and time, the two references for all the ecological aspects. The spatial reference for the restoration of UGI must consider both the urban area (including periurban and municipal areas) and the area of influence of the urban zone, which can extend far away from the city. Most raw materials (water, sand, food, metals) used in cities proceed from rural areas. So, the activities in urban zones highly influence rural areas. Then, restoring the whole system must include the connected urban and rural areas.

This is important to be considered because urban and rural subsystems are in different degree of organization and it is well known in ecology that well organized systems (urban zones) take resources and production from less organized systems (rural zones).

With respect to the spatial consideration, restoration of UGI should also consider that urban zones of a city may have different intensity of use (population density, mobility, services) and that if may be impossible to change significantly the intensively intensified zones of a city. Then, an effective strategy may consist on creating or restoring different types of green sites contributing diverse benefits to the city on the whole.

Finally, the provision of benefits by created or restored sites requires time, in most cases more than a few years. And also maintenance, because UGI sites are made of natural components and should be regulated by as much as possible natural processes. Then, there may be failures in the process of creation or restoration of UGI sites.

The recently passed in the European Parliament Restoration Law will stimulate the restoration of UGI all around European urban zones. It could be an opportunity for considering all these points in order to achieve an effective and efficient creation and restoration of UGI in Europe.

1.4 Objectives of the Doctoral Thesis

1.4.1 Hypothesis

By integrating and optimizing urban green infrastructure into urban planning, the city of Zaragoza can become more resilient to climate change and mitigate its effects, allowing for more sustainable and adaptable urban development. This can only be achieved through environmentally friendly integrated management strategies and, particularly, through enhancing the integration, and promoting the connectivity of green infrastructure into future urban development plans. This proposition constitutes the starting hypothesis of the Doctoral Thesis.

1.4.2 General Objective

The starting point of all this research is to answer a research question: How to better guide urban green infrastructure planning in the city of Zaragoza in order to ameliorate climate change effects?

Therefore, the main goal of this dissertation is to evaluate the urban green infrastructure of Zaragoza and provide recommendations for enhancing the provision of ecosystem services, particularly to fight climate change.

1.4.3 Specific Objectives

The general objective will be addressed through the following specific objectives:

- **Specific objective 1**: Analyze the state of the art of urban green infrastructure in relation with sustainable development.
- **Specific objective 2**: Develop an ecological index to evaluate the UGI of Zaragoza. The index will serve as a qualitative tool to evaluate the naturalness, and ecological functionality of green spaces within the urban environment.
- **Specific objective 3:** To quantify the contribution of different UGI types to the provision of key ES and to identify the relationships between UGI elements and ES delivery. The benefits of UGI for inhabitants, i.e. ES, will be detailed, underscoring the unique advantages UGI brings to the city of Zaragoza.
- **Specific objective 4:** To understand how UGI can act as a buffer against the impacts of climate change. By examining the potential of UGI to mitigate climate change effects, this thesis aims to contribute valuable insights into the planning and design of UGI as a climate-resilient solution for medium sized cities like Zaragoza.

In summary, this research seeks to highlight the relationship between UGI, sustainable development, and climate change resilience in urban environments.

1.5 Study Area

The spatial scope of the research carried out within the framework of this PhD thesis focused primarily on the urban populated area of the municipality of Zaragoza, located northeast of Spain (Figure 1). It is a medium-size city [83], Zaragoza is the capital city (740,938 inhabitants, 973.8 km^2) of Zaragoza Province (972,000 inhabitants; 17,274 km^2) and of the autonomous

community of Aragon (1,332,000 inhabitants; 47,720 km²). The city's North and South poles are seeing the most residential expansion, while certain areas have already undergone urbanization and others are in the process. The climate in Zaragoza is Mediterranean and semiarid. The rainiest seasons are spring (April–May) and autumn (September–November), with summer (July–August) and winter (December–March) experiencing relative droughts. The average annual precipitation is 322 millimeters, although irregularity is high both monthly and annually. Although the Ebro River in Zaragoza became more linear since a century ago, it still has sizable floodplains both upstream and downstream [84]. The city of Zaragoza and its upstream areas are home to extensive floodplains that remain along the Gallego River, a significant tributary. On the other hand, the Huerva River, another tributary, has been completely channeled and predominantly flows underground. A major irrigation water, Canal Imperial, carrying water from the Ebro River diverted 80 km upstream Zaragoza also crosses through Zaragoza city, as well as minor irrigation canals from the Gallego River.

The urban green infrastructure sites (UGIs) in Zaragoza comprise of natural, semi-natural, and man-made areas, which include both land and water ecosystems. While certain UGIs are small and situated in the highly urbanized areas of the city, larger green spaces such as river banks, forests, and meanders are predominantly found in the sub and peri-urban outskirts of the city.

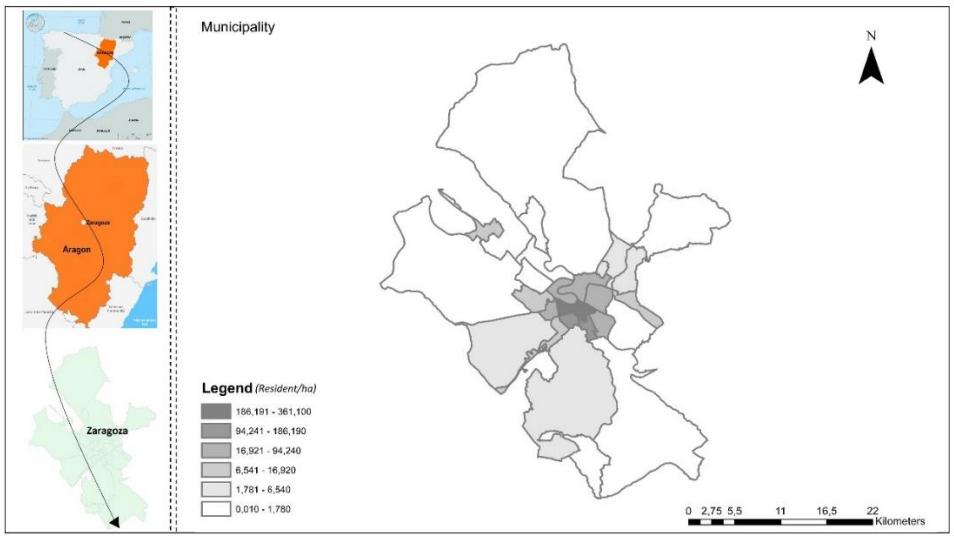


Fig. 3. Study area corresponding to the municipality of Zaragoza (Spain). This map shows the population density of the city.

It is a remarkable case of study for three reasons: 1) It is becoming one of the most populated cities in Spain, with a population nearly reaching 1 million. 2) It contains a wide variety of elements of blue and green infrastructure in the urban and peri urban area, which is interesting to evaluate and study their provisioning services. 3) The municipality of Zaragoza has a goal to make Zaragoza a carbon neutral city in 2030, so this thesis can contribute and give recommendations to achieve this goal.

The Zaragoza UGI is made up of artificial, semi-natural, and natural areas that include both aquatic and terrestrial habitats. The majority of the comparatively vast green areas (river banks, forests, and meanders) are found in the city's peri-urban surrounds. Artificially UGI

elements are smaller in size compared to the natural ones, and are mostly located in the intensively urbanized areas, such as pocket parks, community gardens, urban parks, urban natural parks, green walls, squares, roundabouts, university parks, irrigation canals, and street trees.

1.6 Justification of the Thematic Unity of the Articles

The Doctoral Thesis is made up of 4 scientific articles, quoted in the initial page and collected in section 2 of this document, which are interrelated as a sequential experiment where the results of a paper open the interest for the next one.

The first paper presents a bibliometric review of UGI and its relationship to sustainable development, laying the foundation for the research and knowing what is lacking. The second paper goes deeper into the evaluation of UGI, assessing its naturalness and functioning within the city of Zaragoza. Based on this, the third paper highlights the provision of the ES delivered by the different elements of UGI. Also this paper studied the interrelationship between these services and the structural features of the UGIs and some environmental factors regulating the provision of ES. Finally, in the fourth paper, the relationship between UGI and climate change adaptation was highlighted, focusing on UGI scenario analysis in relation to climate change in the city of Zaragoza. These papers served as a thematic synthesis that advanced the knowledge of UGI's role in combating climate change, as well as providing practical recommendations for city planners and policy makers (Figure 4).

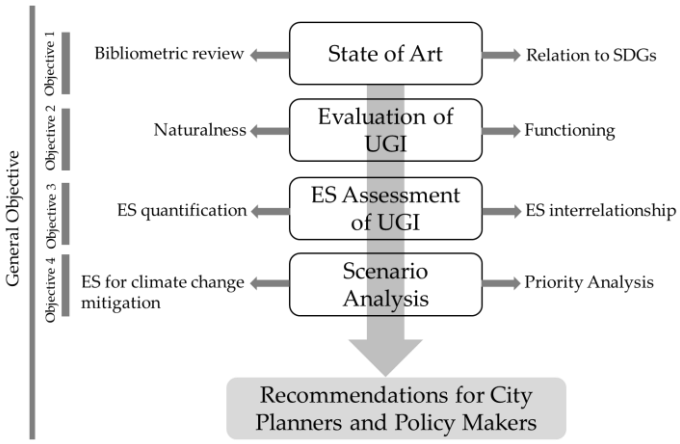


Fig. 4. Diagram illustrating the different chapters of this study

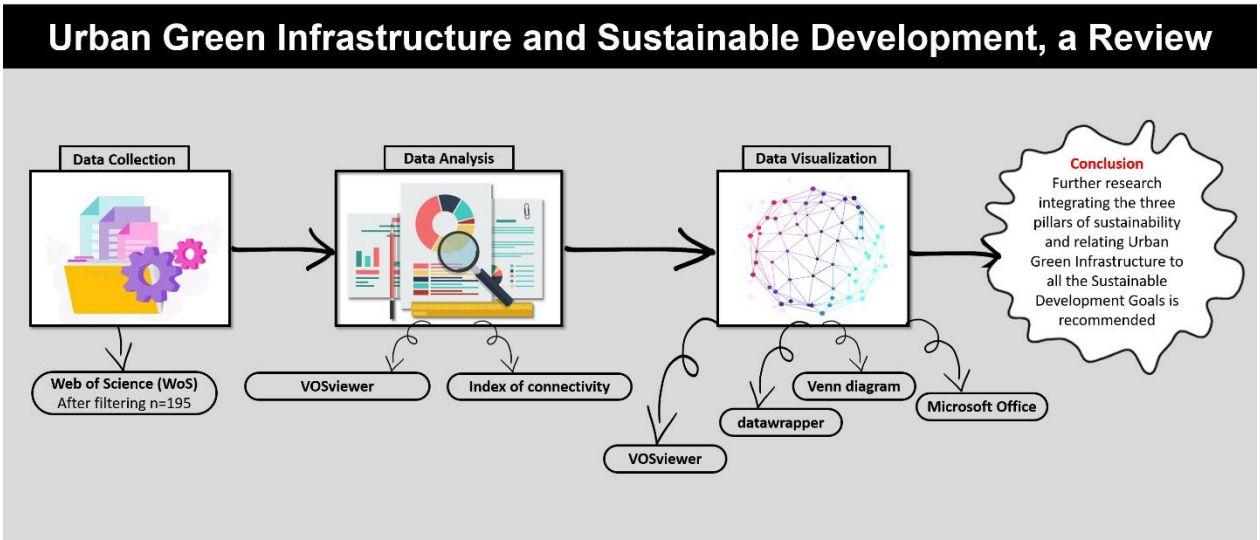
1.7 General Methodology

- **Theoretical framework:** The thesis initiates with a comprehensive literature review aimed at understanding urban green infrastructure and its relationship to sustainable development, laying the foundation for the research and knowing what is lacking. This review, outlined in the first article, served as the foundation for subsequent investigations, aligning with Specific Objective 1.
- **Methodological frameworks:** In the first paper, VOSViewer software was used to do the bibliometric review analysis. VOSViewer is used in review articles about green infrastructure (e.g. D P Retno et al, 2020. Mirici, 2022. [85-86]), to visualize relationships between different elements such as authors, keywords, or co-citations. For the second paper, ArcGIS used for spatial analysis and green infrastructure design (e.g.

Rodríguez-Espinosa et al. 2020 [87]), and Google Earth were an important tool to calculate the area of naturalness and functioning. Also ArcGIS was used in the third paper to specify the sampled UGI sites, and in the fourth paper to analyze the spatial characteristics of ES supply within the study area. For the second, third and fourth paper, statistical analysis was conducted using RStudio, a powerful software environment for statistical computing and graphics facilitating robust data analysis and interpretation. RStudio was used to visualize principal components analysis (PCA) graphs, and conduct multivariate analysis. It is widely used in publications on green infrastructure (e.g. Fauk et Schneider, 2023 [88]). In the last paper, a semi-structured survey was sent to experts. Through surveys, we have been able to capture the diverse perspectives, experiences, and preferences of various stakeholders involved in green infrastructure initiatives (e.g. Santo-Tomás Muro et al. 2020. [89]). In our study, the experts were chosen for their dedication to sustainable urban development, which is evident in their involvement in contributing to scientific publications, and engaging in meetings with Zaragoza residents to gather ideas and opinions on city development.

2. COMPENDIUM OF PUBLICATIONS

ARTICLE 1: Hanna, E.; Comín, F.A. Urban Green Infrastructure and Sustainable Development: A Review. Sustainability 2021, 13, 11498 https://doi.org/10.3390/su132011498



sustainability

MDPI

Review

Urban Green Infrastructure and Sustainable Development: A Review

Elie Hanna [1,2] and Francisco A. Comín [2,*]

[1] Departamento de Ciencias Agrarias y del Medio Natural, Escuela Politécnica Superior, Universidad de Zaragoza, 22071 Huesca, Spain; 812719@unizar.com
[2] Instituto Pirenaico de Ecología, Consejo Superior de Investigaciones Científicas-CSIC, 50059 Zaragoza, Spain
* Correspondence: comin@ipe.csic.es; Tel.: +34-976-369-393 (ext. 880061)

Abstract: Urban green infrastructure (UGI) can alleviate many of the problems that the growing urban population is facing. This study performed a literature review about UGI and sustainable development (SD) using the Web of Science (WoS) and the software VOSviewer. Of 195 papers selected, 89 are qualitative, focusing on theoretical approaches and design; equally, 89 are quantitative, dealing with metrics and spatial analysis and 17 combined both approaches. A high connectivity between "green infrastructure", "ecosystem services", "urban planning" and "sustainable development" was observed. Only 39 of the documents embrace environmental, social and economic aspects. Most of the papers are related to Sustainable Development Goal (SDG) 11, "to make cities inclusive, safe, resilient and sustainable" and SDG 15, "protect, restore and promote sustainable use of terrestrial ecosystems". Further research integrating the three pillars of sustainability and relating UGI to all the SDGs is recommended.

Keywords: urban green infrastructure; literature review; sustainable development goals

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1. Introduction

Urban green infrastructure (UGI) is progressively claimed as an essential structural part of cities [1], playing a key role in the sustainable development (SD) of planet Earth, because most of the human population is now living in urban zones. The UGI of a city is made up of different types of systems more or less connected with each other. The essential components of UGI are natural elements (plants, animals, water, soil and micro-organisms etc.) structured in a variety of forms (e.g., urban squares, street tree lines, parks and horticultural gardens). These are the same components structuring natural ecosystems and making them perform ecological functions, and thus provide ecosystem services (ES). However, the urban oriented design and construction of UGI and the occupation and use of natural ecosystems for urban purposes incorporate artificial components to the UGI. This causes a decrease in the provision of regulating services but an increase of recreational services, which are respectively related to the fulfillment and the limitations of natural ecological functions. In other words, UGI can contribute substantially to the SD of cities through the provision of ES and avoid disservices [2–5].

The connectivity between UGI sites is essential to provide benefits for persons in a city. In fact the network of UGI and its distribution in the urban zone is an important aspect of urban planning [6]. The growth of the cities is frequently a dilemma between the conservation and the urbanization of natural environments. As far as new natural areas are urbanized, loss of ES takes place while urban living facilities for humans increases. As a consequence of the increasing interest in SD, urban green infrastructure design, provision, maintenance, conservation and restoration are being more recognized as critical components of any holistic and realistic strategy for urban sustainability [7,8]. Urban zones acknowledged their huge contribution to global changes and increase their interest in contributing to sustainability by reducing the emission of greenhouse gases and increasing

their inhabitants' welfare [9]. Among other actions, establishing a well-structured UGI is one of the most common challenges for urban zones to contribute to these purposes.

Many different types of UGI exist and their typology has been a matter of study from different points of view [10]. Additionally, different indicators have been proposed to analyze the components and values of UGI [11]. The methodologies to study UGI vary in relation to the subject of interest. The contribution of UGI to improve people's health has been shown clearly [12,13]. Functions and services are related through a conceptual approach [14]. The spatial analysis of UGI was used by González-Duque and Panagopoulos [15], in relation to social aspects. Spatial analysis, along with surveys and interviews, was used by Meerow for land use planning [16]. The evaluation of ES was used to support the values of UGI [17]. Several research lines have been suggested to progress the understanding between urban biodiversity, ecosystem functions and services [18]. People´s preferences of UGI density were studied by Suppakittpaisarn et al. [19].

Therefore, UGI plays multiple roles in both city and global scales and is a subject of study of increasing interest. Many authors performed an intellectual exercise proposing theoretical frameworks and interpretation of the role of UGI for the ecology of cities to improve planning aspects in line with sustainability objectives [14]. Most frequently, all these aspects are approached separately while studying UGI characteristics. It is difficult to take a holistic approach because of the required specialization to study any of the mentioned aspects and because of the huge effort required for the integration of the significant number of aspects involved in UGI.

In this paper, we review how UGI research is approached in relation to SD through: (i) a literature review focusing on disentangling the methodological aspects of UGI research after an analysis of the relationships between topics and authors of the reviewed documents; (ii) an observation of the distribution of the topics of interest of the documents in relation to the three major pillars of sustainability (environmental, social, economic). Thereafter, (iii) a review on the relation between the subjects of interest of the searched documents on UGI and the United Nations Sustainable Development Goals (SDGs) was performed.

2. Materials and Methods

The steps followed for the review process and data analysis are schematized in Figure S1 in supplementary material.

2.1. Literature Search

The literature review was based on the results of a search conducted at Web of Science (WoS) on 27 April 2021 at 16:00 h using the topic keywords "Urban Green Infrastructure" AND "Sustainable development" for 1992–2020. The 663 obtained documents included journal articles and proceedings documents. Then, we excluded "book chapters" from Web of Science, in addition to documents referring to disciplines that were alien to our search interests ("energies", "lecture notes in civil engineering", "horticulture", "mathematics interdisciplinary applications", "materials science multidisciplinary", "mechanics", "transportation", "operations research management science", "engineering electrical electronic", "advanced engineering forum", "frontiers in psychology", "globalization and health" and "heliyon") and documents not written in English. Subsequently, the list of documents was reduced to 318.

Thereafter, we performed manual filtering, excluding all the articles not including the two words "green infrastructure" neither in the title nor in the abstract, and the number went down to 197. One more article was excluded because it was published in 2021 (not in the specified period of research) and another one was removed because it was a duplicate. The final number of articles used for further analysis was reduced to 195. The spatial and time trends of the research topics were obtained from the analysis of results tool of WoS.

In order to disentangle the scientific approaches used in the searched documents, they were classified as theoretical if they presented qualitative considerations or frameworks, and practical if they used quantitative data after reading the abstracts. In case of doubt,

the paper was reviewed in full. Mixed documents were those which included a qualitative approach as well as data analysis of a case study. The documents in these three blocks were then grouped according to more specific research interests and methods used. Particular attention was paid to those documents using or focusing on the evaluation of ES because of the strong relationship between ES and the topics of interest of this literature search.

2.2. Bibliometric Analysis

VOSviewer 1.6.16 was used for the bibliometric analysis. Vosviewer is a software tool for building and visualizing bibliometric networks specialized in the graphical representation of bibliometric maps. It provides different ways to display networks and allows close examination of a map via the zoom, scroll and search functions [20]. Moreover, by dealing with a large number of items, the cluster display can provide us with a clear overview of the network structure. Thus, VOSviewer was used to obtain bibliometric maps that help analyze the links between topics in order to understand how UGI and SD are linked.

The cluster display is applied in this research to have a better structural view of the networks. In a map, each unit is presented as a node. It can be a journal, a category, an author, an article or a keyword. The distance between the nodes shows their relationship. If two nodes are displayed close to each other, it can be interpreted that they are strongly related. Links between nodes represent the direct co-occurrence and co-citation. The strength of the links is proportional to the co-occurrence or co-citation frequency. Nodes related to each other with stronger links can be grouped into one cluster, and each cluster is assigned one color. It can be interpreted that the units within a cluster share a high homogeneity, while the units in different clusters are heterogeneous. With the cluster display, an identification can be made of the intellectual structure of UGI and SD research from several perspectives [21].

Firstly, after uploading a text WoS file into VOSviewer, a bibliometric analysis was conducted, which accounted for co-occurrence as analysis type and authors keywords as a unit of analysis. The software produced a superimposed view, with colors applied to the authors' keywords by year of publications. A map of 704 authors' keywords was illustrated, then an acceptable and readable result was obtained after the analysis of the authors' keywords with five being the number of a minimum occurrence of keywords (keywords that are repeated less than five times are excluded from the map), which produced a map with 24 easily identifiable keywords. Co-occurrence is when two or more keywords occur together in the same paper, thus each keyword is represented by a circle; the bigger the circle, the more the keyword occurs in the papers. Keywords that have a strong occurance together will be linked together. The link strength, which indicates the number of publications in which two keywords occur together, will be high (compared to other keywords), and the distance between these two keywords will be short. In reverse, keywords that occur together weakly will have a low link strength number and the distance between them will be high. Figure S2 shows an idealized example of this type of results from the co-occurrence analysis of keywords. K1 (Keyword 1) has the biggest circle, hence it is the keyword occurring most in the publications; the closest keyword to K1 is K2, they have a link strength of 12, meaning K1 and K2 occurred together in 12 papers indicating that there is mutual interest of research on the topics represented by K1 and K2.; K4 is the farthest from K1, so they have a link strength of 3, meaning that they appeared together as keywords only in 3 papers and that there was not much interest on joint research on these two topics, K4 and K1.

The gamma index of connectance is a measure of connectivity among nodes (subjects or topics of interest) of a network: the number of links divided by the total number of possible links [22]. It can be applied to both the full network and to a specific node of the network. The value of gamma connectance ranges between 0 and 1, where a value of 1 indicates a completely connected network/node with the rest of nodes and 0 indicates that there is not any node of the network connected to each other/a particular node is not connected to any other.

This probability index uses the combination formula (combinations of n nodes or topics taken, k, at a time without repetition) to calculate the number of possible combinations of the 24 subjects of interest selected as a network or separately for each of them; it is the maximum or potential number of links of a node or of the full set of nodes in a network [23,24]. Thus, it is the number of combinations of n nodes taken 2 at a time without repetition C = n (n − 1)/k (K − 1), and in our case n = 24 (the number of nodes/topics selected) taken by groups of k = 2. This gives 276 potential links between nodes in our network. Then, we used the actual number of links of each node (topic) divided by the potential number of links as a measure of connectivity for each node, and also for the full network as mentioned above. So, in our case, this index of connectivity for each node can range [0–0.083] ((0/276)–(23/276)) if, respectively, it is not connected to any other and if that node/topic is connected to all the other 23. For the full network, the index is useful to know the state of present connectivity among the nodes of the network (among the topics or subjects of interest of the selected network of 24 topics).

Second, a bibliometric analysis was conducted using VOSviewer which encompasses co-authorship as a type of analysis, and authors as a unit of analysis. It considers the number of occurrences of 708 authors and the links of co-authorship between them in order to know the relationships among authors and citations per author, among other aspects. Authors that cluster together are coauthors of papers, the closer the authors are to each other, and the more they published together. In Figure S2, the author 1 (A1), has the biggest circle, hence this author has published the highest number of articles on the searched subject; the closest author to A1 is A4, so these two authors have published 6 publications together; A2 is located the farthest from A1 but still connected, they have published together 1 publication connectance. A6 did not publish with anyone, that is why this author is not linked to any other author.

Third, a bibliometric analysis was performed with VOSviewer that considers citation as a type of analysis for the purpose of knowing the relationships among citations of documents and their citation ranking. A citation link is a link between two items where one item (document, publication, journal or institute) cites the other. In general, the closer two items are located to each other, the stronger their relationship. In Figure S2, D1, (2018) (Document 1, published in 2018) with the biggest circle, is the most cited document and it is also the most cited document between the authors of this idealized exercise. D2 (2019) is the closest document to D1, which means that D1 and D2 deal with related topics. D5 (2019) also has a big circle, but it is not connected to any other author. This implies that no other document in this exercise mentioned D5 (2019) but since it has a big circle, D5 is mentioned by other authors from a different subject outside the subject of interest of this idealized example.

2.3. Spatial Distribution of the Documents

Datawrapper software was used, combined with the analysis option of VOSviewer, to obtain the number of documents per country of affiliation of the first author and produce a worldwide map of the 195 documents distributed by country, which will be used to describe differences in the publication of papers between countries [25].

3. Results

3.1. Distribution of Publications through Time and Space

Before 2005, no document dealing with UGI and SD was obtained through our search. Consequently, three phases can be distinguished with respect to the number of documents published per year (Figure 1). At the beginning of phase 1 (2005–2012) the Millennium Ecosystem Assessment was published. Furthermore, the paper by Li et al. [26] was published receiving the highest number of citations (213 citations). In this period, the annual number of documents did not increase until the year 2013, when phase 2 (2013–2017) started, just one year after the United Nations Conference on Sustainable Development Rio+20 in 2012. Then, the number of published documents increased from 4 to 10 per year,

including the highly cited (94 citations) paper by Collier [27]. During this phase 2, there was a remarkable increase of published articles (57), especially in the last 2 years 2016–2017, including the second most cited paper (107 citations) by Liu et al. [28]. Then, phase 3 started in 2018 with an explosive increase in the number of papers per year (25–30), simultaneously with the publication of the forth most cited article (92 citations) by Chan et al. [29].

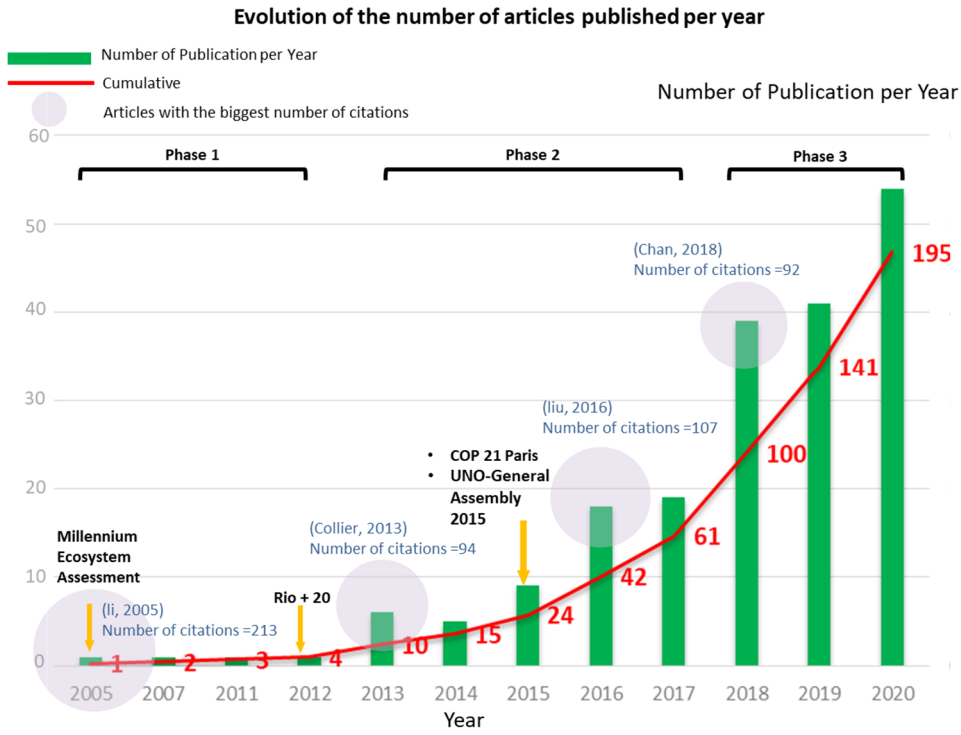

Figure 1. Yearly output of articles from 1992 to 2020, the oldest article appeared in 2005. The circles represent the articles with the biggest number of citations. The bigger the circle, the more it is cited.

The distribution of documents per country of affiliation of the first author shows the typical agglomeration of papers in scientifically powerful countries, such as the USA and China, which also accumulate problems of urban sprawl [30]. If we consider Europe as a socioeconomic unit, it contributes an outstanding number of papers, over other geographical regions (Figure S3). The number of papers from the rest of the regions/countries is much lower, except for Australia which accumulates an intermediate number, likely in relation to the scientific development of this country and the recent enlargement of its urban zones [31].

3.2. Disentangling the Methodological Aspects of UGI and SD Research

The same number of documents that were identified in the search focused on qualitative (89) and quantitative (89) aspects, while a low number (17) combined both approaches (Figure S4). Most qualitative documents (those not presenting quantitative data) present theoretical aspects, as more or less detailed descriptions of subjects of interest and conceptual frameworks, e.g., describing the role of ecosystem services in urban ecological infrastructure [32], proposing five ways of water management in arid urban zones [33]. Between the qualitative documents, 29 focused on design aspects such as landscape architecture and connectivity in relation to UGI (e.g., Cengiz and Boz [34]), urban sprawl (e.g., Zhang, L and Huang [35]) and UGI recovery (e.g., Blau et al. [36]) and 21 are literature reviews focusing on different aspects related to UGI.

Most quantitative documents (62) focused on spatial analysis. They are papers that use mapping through GIS or remote sensing to describe and analyze topics such as landscape connectivity (e.g., Niedźwiecka-Filipiak et al. [37]), urban sprawl (e.g., Gavrilidis et al. [38]),

assessing urban heat island (e.g., Marando et al. [39]), water management (e.g., Wong et al.; Kuller et al. [40,41]) and related subjects. The remaining 27 quantitative papers focused on metrics: quantitatively evaluating variables of UGI and SD such as assessment of green development (e.g., Wu et al. [42]), estimating the value of UGI or ES using cost-benefit analysis of UGI (e.g., Sutton and Anderson [43]) and analyzing the economic sustainability in storm water urban catchments (e.g., Boguniewicz-Zabłocka and Capodaglio [44]). It is also noticeable that between these 27 articles, 8 of them (the biggest number between the 27 articles) use cost-benefit analysis in their methodology (e.g., W. Liu et al. [28]). So, quantitative documents are mostly devoted to environmental and economic aspects of UGI and SD. A relatively high number, 26 of the 89 quantitative articles, directly target ES, ranging from regulating urban heat (e.g., Wu et al. [45]) and flooding (e.g., Huera Lucero et al. [46]) to citizens' recreation (e.g., Sun et al. [47]).

Of the 17 papers combining a qualitative and a quantitative approach (Figure S4), 12 performed a literature review and a spatial analysis (e.g., Liu et al. [48]), and 5 performed a literature review and a metrics analysis (e.g., Mell [49]). The papers combining both approaches are dealing with the association between the distribution of urban trees and socioeconomic status aspects (e.g., Cruz-Sandoval et al. [50]), water conservation (e.g., Monteiro and Ferreira [51]), public spaces and climate change (e.g., Vukmirovic et al. [52]) on the one hand, and people satisfaction with green infrastructure (e.g., Parker and Simpson [53]) on the other hand.

3.3. The Interest on Sustainability

Only 20%, 39 of the 195 papers, take a holistic approach combining the three pillars of sustainability (environmental, social and economic) in their studies. Between the 195 papers, 111 have any interest on just one of these aspects: 81 deal with environmental topics, 19 deal with social aspects and 9 with economic aspects. Then, 23 documents combine two aspects: 19 follow a socioenvironmental approach; 2 take a socioeconomic approach, and 2 take an environmental and economic perspective. Additionally, 39 documents deal with all three aspects. Englobing all these elements of sustainability, 24 is the number of articles that speak about policy and decision making (Figure S5).

3.4. Disentangling Subjects of Interest and Authorship Relationships

The bibliometric analysis performed with VOSviewer showed that 24 keywords were used in at least five papers (Table 1). "Green infrastructure", "ecosystem services", "sustainable development", "urban planning" and "climate change" were the most used keywords by the authors to represent the subjects of interest of their papers. These five keywords had the highest number of links with other keywords among the 24 most used (Table 1). "Green infrastructure" (GI) is represented with the biggest circle after the co-ocurrence analysis (Figure 2), it occurred in 61 papers. The closest keyword to GI is "ecosystem services" which occurred in 34 papers. GI, ES and urban planning share a relatively high connectivity (over 0, 05) (Table 1) and the strength of the link is equal to 11, meaning that GI and ES and urban planning occurred together in 11 papers. GI and "sustainable development" and "climate change" occurred 12 and 10 times, respectively, as keywords in papers and share an intermediate connectivity =(0.04). The remaining 19 keywords had a relatively low connectivity (lower than 0.04) to the other key words. All this indicates that there is still a high potential for linking topics of research related to UGI and SD.

Table 1. The 24 keywords, representing topics of interest, used at least in 5 of the 195 searched documents with the number of links (documents) to each other and their index of connectivity.

Topic	Number of Links	Number of Links/Combination Formulation
Green infrastructure	20	0.072
Ecosystem services	16	0.058
Urban planning	14	0.051
Sustainable development	13	0.047
Climate change	12	0.043
Sustainability	10	0.036
China	9	0.033
Sustainable cities	7	0.025
Multifunctionality	7	0.025
Stormwater management	6	0.022
Nature-based solutions	6	0.022
Low impact development	6	0.022
Sponge city	6	0.022
Urban	6	0.022
Urban development	6	0.022
Urban green infrastructure	5	0.018
Planning	5	0.018
Urban sustainability	5	0.018
Landscape connectivity	5	0.018
Urban ecosystem services	5	0.018
Urbanization	5	0.018
Green space	4	0.014
Urban ecology	4	0.014
Sustainable urban development	2	0.007

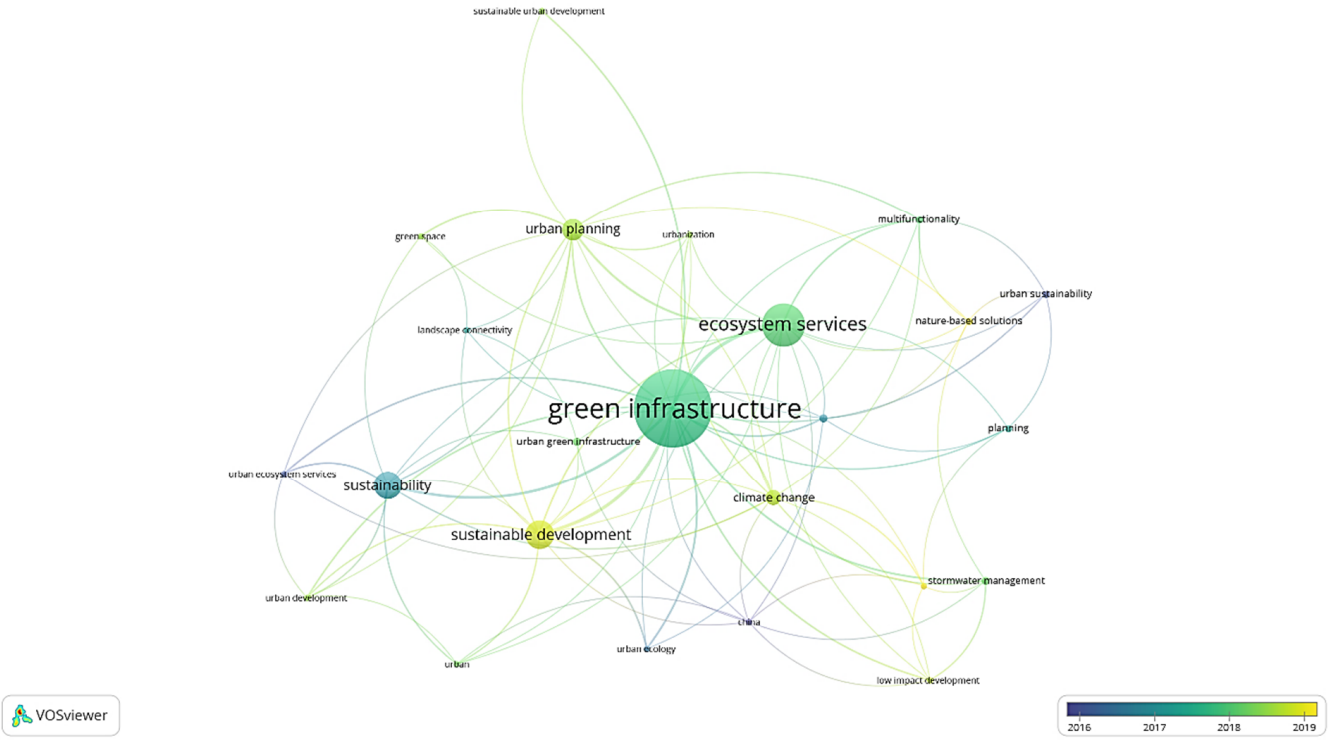

Figure 2. Keywords most frequently used in the articles reviewed. Those in colder colors appeared in the earlier years and those in warmer colors later. Bigger circles correspond to the most used keywords.

Logically, "green infrastructure" and "sustainable development" should be the keywords linked to most keywords as they were part of the words used for the literature search but this is arguable as the analysis showed different results. "Green infrastructure" must be understood as "urban green infrastructure" as it is in the context of urban zones that the search was made. "Sustainable development" is connected to many of the keywords; however, it is not connected to important topics such as urban sustainability, sustainable urban development, urban ecosystem services, storm water management or planning.

The occurrence of keywords on sustainable development (in 23 papers) and climate change (in 12 papers) are dominant in recent years (2019–2020) contrary to topics such as green infrastructure (in 61 papers) and sustainability (in 22 papers) which were dominant previously (2016–2018), nature based solutions occurred in 6 papers during 2019–2020 (Figure 2).

The index of connectivity (Ducrue and Rodrigue, [22]) for the full network of topics is 0.65, which confirms the idea that this network of topics still has a high potential for linking subjects of interest in relation to UGI and SD.

The results of the bibliometric analysis that considers the most cited papers between the 195 documents searched showed that Li et al. [26] had the highest number of citations (213) and, correspondingly, the biggest circle in Figure S6 (the above figure). The approach in this paper is qualitative, aiming to develop a comprehensive conceptual framework for urban greening of the Beijing Province in China, based on landscape ecological principles. Following the qualitative approach, the second article with the highest number of citations (94) in the VOSviewer map is Collier et al. [27], aiming to explain the sponge city concept and its development, which considers the limitation of urban sprawl through UGI planning.

Even though Li et al. [26] is the most cited document, there are only 2 other documents linked to it. This means that this paper is not highly cited among the authors of this literature review, but is cited in documents not included in this literature. The same can be said for the document by Collier et al. [27] (Figure S6).

The first most cited document with a quantitative approach (Liu et al. [28]) is the second most cited (107) between all the 195 documents searched (qualitative, quantitative and mixed). It presents a spatial–temporal assessment of urbanization impacts on ecosystem services. Badiu [54] is the second most cited article (61) between the quantitative documents; it aimed to assess urban green space (UGS) per capita. Both articles used spatial analysis in their methodology.

The same figure, but without the unconnected authors (Figure S6), illustrates that the most cited paper obtained in our review is by Newell et al. [55], which is linked to 6 other documents, meaning that this paper was cited by 6 documents of our literature review. Their paper analyzes alley greening programs in seven cities in the United States using the lens of sustainability planning. It presents a mixed methodology, including a literature review and a spatial analysis to indicate that most alley greening programs are narrowly oriented towards storm water management.

There were 708 authors of the 195 articles. However, only 88 authors (12.4%) are highly connected to each other, which is shown by 18 big clusters connected between others (Figure S7). This means that these authors worked and published together. The rest of the authors (87.6%) form clusters but they are not connected to any other of the highly connected clusters. The author Dagmar Haase has the highest number of papers (5) written on UGI and SD, followed by Artmann Artina with 4 documents.

The remarkable cluster is the red one (Figure S7). It consisted of 23 authors who worked closely together, their focus is on nature, city and sustainability. These authors do not live in the same country nor on the same continent, but the majority of them live in countries where English is the dominant language, such countries are South Africa, Canada, the USA, Sweden and Australia. One of the articles they published [56] proposes modes of operation encompassing policy, planning and management processes, that seek to transform the use of old nonsustainable practices and design new urban systems in ways that diversify their functions, anticipate new uses and enhance adaptability, to better meet

the social, economic and ecological needs of cities under conditions of deep uncertainty about the future. This paper is a qualitative one, working on the design of new urban environments in order to contribute to successful implementation of SDG11 and the New Urban Agenda (https://unhabitat.org/ accessed on 21 July 2021).

4. Discussion

4.1. Disentangling Methodological Aspects of UGI and SD Research

This work provides an overview of published papers relating UGI and SD. Linking both of them is of major interest because of the key role that urban areas with a well-structured GI can play in contributing to sustainable development [57]. An increase in the number of papers on this subject of interest was observed after the publication of the Millennium Ecosystem Assessment (2005) and, more recently, after the United Nations launched the Sustainable Development Goals (UNO-General Assembly 2015). It could seem that since 2005, international events and conferences promoting attention and action in favor of nature conservation and sustainable development stimulated research on related topics. However, the opposite also happens as many global strategies and challenges arise after scientific research on socioecological problems attracted attention to them [58]. Thus, most likely, both processes feed into each other.

The fact that half of the documents of the searched series contained a theoretical approach seems to indicate a dedicated interest by many authors to establish conceptual principles and frameworks in order to address the study of this topic. After this, it is foreseen that the number of quantitative works providing empirical information will increase more in the future and that generalizations providing advanced insights to progress the study of UGI and SD will take longer if a usual model of science progress accumulating information progressively up to synthetizing an innovative framework or theory is going to proceed [59,60].

This review shows (Figure S4) that there is a high variety of quantitative topics researching UGI and SD, but there is a lack of integrative and holistic studies, thus the need for a comprehensive approach, embracing the many aspects involved in this subject of interest. In general, a quantitative approach, providing data of measured variables is more convincing than a qualitative one. However, quantitative studies focus on few variables because of the great efforts required to measure variables and analyze data compared to theoretical approaches. Then, in the near future quantitative studies encompassing a range of aspects and many variables should be performed and should come up with holistic overviews of UGI and SD for an urban zone, a series of urban sites or globally. This will require further accumulation of data and synthesis but will contribute to balancing the uneven distribution of information with respect to the three pillars of sustainable development (Figure S5). This will also provide insights for planning and implementing UGI in such a way that improve and most efficiently contribute to the SD of urban zones.

It is also recommended to increase research relating to UGI characteristics and people´s perception (e.g., Fischer and Kowarik [61]), as the ultimate goal of studying and applying results of UGI and SD research is to provide a better quality of life for the beneficiaries, inhabitants and visitors of urban zones, and contribute to regional and global improvements of ecosystem services and SD. In fact, among the documents approaching with quantitative metrics the study of UGI and SD, 27 of them estimate the values of variables such as watercourse suitability (e.g., Simperler et al. [62]) and urban foraging impact on human health and well-being (e.g., Fischer and Kowarik [61]). Additionally, 8 of them (e.g., Hamann et al. [63]) used cost-benefit analysis in their articles to estimate the value of UGI. This indicates a relatively high interest in estimating the economic value of UGI, in spite of the fact that there are alternatives to cost-benefit analysis which can be better, or at least complementary, to quantify the benefits of UGI as providers of ecosystem services and its relation to sustainability [64] and offer an opportunity for future research.

Authorship bibliometric analysis can also provide insight into the intellectual structure of UGI and SD research. The authors that published together are located close to each other

on the map and grouped into one cluster (Figure S7). As only 12% of the authors shared a high connectance between each other, we argue that there is not yet a high experience of sharing between authors on this subject, which is also indicated by the big number of clusters unconnected. This opens a window for the possibility of greater opportunities for collaboration in the future. The light green cluster on the top left belongs to Chinese authors working and publishing together. This cluster is not connected to any other cluster even though it contains the authors of the most cited article ([26]). It seems likely that authors from different countries are not connecting enough to each other to perform research and publish together. As it was said, clusters are made of authors who published together most likely on related subjects, therefore, small clusters (less than 7 authors) in the map provide the chance for better collaboration on other topics that might be of interest in the future. Such topics could be sustainable urbanism, ecological infrastructure, green streets, for example, and all these involving social and economic aspects, as stated above.

The outstanding number of documents corresponding to three countries, the USA with 82.66% of its population living in urban areas in 2019 [65], China, where urban sprawl is now a major issue of research interest and development concern [66], and Europe with a long history of urban development, indicates the interest of researchers in these countries to contribute to improving conditions where UGI and SD presented higher deficiencies. Then, it is recommended to increase the collaboration among authors from different countries and continents in the future.

The huge difference in the number of papers between the USA, Europe, China and Australia, on the one side, and Central-South America, Africa and SE Asia, on the other side, reflects the usual difference of publications between these two groups of regions. By no means, does this indicate a difference in the capacity or interest of study in these regions, which also share common urbanizing problems with other regions of the world. In fact, a few papers by authors from countries in Africa, South America and SE Asia show excellent theoretical and practical approaches and contributions to the study of UGI and sustainable development. In addition, it is quite frequent that many authors from these regions do not publish in journals included in Web of Science and other databases (e.g., Andrade et al., Ramyar and Zarghami [67,68]).

4.2. Disentangling Relationships among Topics of Interest

The low and heterogeneous connectivity between topics (keywords) shown by the indicators used (number of links, connectivity index for both the full network of topics and for most topics) indicates that there is still a high potential for linking subjects of interest in relation to UGI and SD. So, there is an opportunity for many more topics to be researched in relation to UGI and SD and increase the links in the network of topics (Figure 2). Likely, the agglomeration (Figure S7) of authors will decrease; consequently, there will be more authors and clusters that will be more evenly distributed among authors. Additionally, it is important to note that even though this research was about UGI and SD, the results showed a high connectance between GI and ES (11 papers) and that ES and SD occurred together only in 2 papers, signaling that the path of SD needs to pass through GI providing the necessary ES to achieve the goal of sustainability, or at least that the evaluation of ES will be a major tool for research on UGI and SD studies.

Combining the three major pillars of sustainability (environmental, economic and social) in an integrated way to study UGI and SD is a desirable approach, and not only for this particular issue [69]. However, we observed few papers (20%) including the three pillars in their methods, while the majority focuses on environmental topics (81). This bias is likely due to the longer tradition of studying environmental issues in relation to UGI, which is made of natural components and also the stress put on urban zones to adapt to climate change (e.g., Wang and Pei [70]). In any case, the papers integrating the three pillars of sustainability focus on topics such as the application of green infrastructure to sustainable cities (e.g., Cengiz and Boz [34]), or just to better explain the role of UGI in urban zones (e.g., J. Wang and Banzhaf, [71]). Overall, these results indicate that there is

a need for more quantitative publications taking a holistic approach in valuing UGI and their ES in relation to SD.

As our review focuses on UGI and SD, it is supposed that published research on this subject of interest should be linked to SDGs. Reviewing the topics of the searched documents, we observed that most topics (sum of occurrence of the numbers in the boxes of the topics = 117) (Figure 3) of our search were related to SDG 15 (life on land: promote sustainable use of terrestrial ecosystems). In the second place, are the topics (sum of occurrence = 97) that are related to SDG 11 (make cities and human settlements inclusive, safe, resilient and sustainable). Followed by topics (sum of occurrence = 26) that are related to SDG 16 (promote peaceful and inclusive societies for sustainable development), and the topics (sum of occurrence = 17) that are associated to SDG 13 (take urgent action to combat climate change and its impacts). A much lower number of topics are related to SDGs dealing with social aspects, such as SDG 1 (sum of occurrence = 12), SDG 2 (sum of occurrence = 12), SDG 3 (sum of occurrence = 5) and SDG 6 (sum of occurrence = 7). However, the most outstanding number of topics (sum of occurrence = 117) is related to SDG 15, which under its general label (protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss) encompasses environmental challenges relative to providing protection for all terrestrial ecosystems, enhance sustainable management, reduce flooding impacts and land degradation, improve air quality and waste management. It is remarkable that few documents of the searched series had as a subject of interest any topic related to the SDGs that are mainly focused on social aspects, such as SDG 1 (no poverty) and SDG 2 (zero hunger) which are challenging issues as many homeless live on urban UGI in many cities and some UG sites, such as urban horticultural zones, could provide food in cities. In any case, most of the UN SDGs are not approached by any of the papers in our selected series of 195 documents (Figure 3). This offers an opportunity for researchers to perform more studies and to publish documents linking UGI and the still missing topics of SDGs, which are mostly related to social aspects.

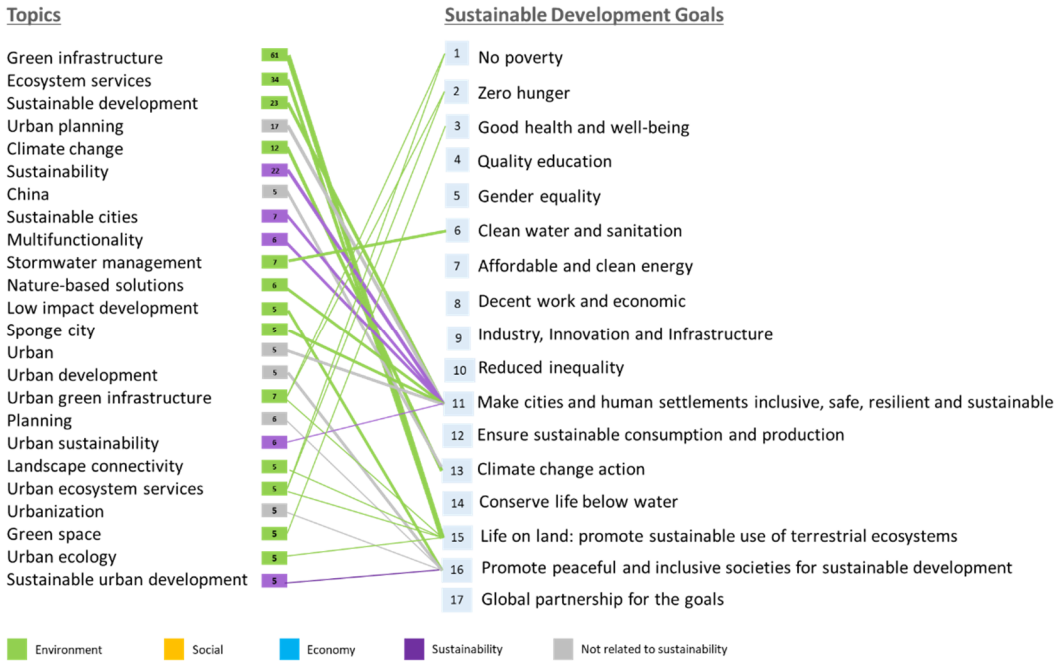

Figure 3. Correspondences between topics of the series of documents searched in this review and SDGs. The width of the line is related to the number of co-occurrences, the numbers in the boxes of the topics/keywords are the number of co-occurrence of these keywords (authors' keywords) in the 195 articles.

This review may be limited in scope as there may be works focusing on UGI and SD from different points of view (e.g., energy, mobility, engineering, transportation, hydraulics). Sustainable development is not only dependent on UGI but there are other aspects that are very important because sustainable development is also related to human and environmental health, transportation and social issues. Additionally, specific searches will be necessary for deeper analysis and reviews since the focus of this study was only reviewing the research performed on UGI and SD. More detailed reviews in other databases may provide further insights into this subject of interest. In any case, the results presented here offer an overview of the present situation of research works on UGI and SD. The increasing annual rate of publication of documents observed shows that UGI in relation to SD will be a crucial issue in multiple academic fields, especially in planning urban zones, which implies a promising future for UGI and SD research.

5. Conclusions

The study of UGI and SD is still in the early stages, as most of the published documents are offering theoretical approaches. More studies providing quantitative information on the many topics under UGI and SD will increase the fundamentals for stronger frameworks linking UGI and SD in the near future.

Most published documents on UGI and SD focus on limited environmental, economic or social aspects. Approaches integrating the three pillars of sustainability are required to further progress UGI planning and implementation and, consequently, to improve the contribution of urban areas to sustainable development. Collaborative research between researchers of advanced countries and other countries will contribute significantly to the SD of urban areas locally and globally.

Most topics of interest in the literature reviewed are related to the Sustainable Development Goals (SDGs) 11, 13, 15 and 16. However, there is very little information on the relationships between UGI and SDGs 1, 2, 4, 5, 7, 8, 9, 10, 12, 14 and 17. Further innovative research should depend on the role of UGI on these less studied SDGs. This will provide insights and key information to accomplish SDGs in urban zones through planning and implementing UGI.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su132011498/s1, Figure S1: Steps performed for the literature review following the PRISMA model and data analysis and visualization after VOSviewer, Figure S2: Above: Idealized network of 4 keywords (K) after VOSviewer. The numbers indicate the strength of the links between two keywords (the number of publications in which the two keywords linked occur). Middle: Idealized network of 6 authors (A) after VOSviewer. The numbers indicate the strength of the link between two authors (the number of papers coauthored). Below: Idealized network of citations of documents (D) after VOSviewer (D1 means Document 1), Figure S3: The distribution of the 195 articles per countries, Figure S4: Disentangling the approaches of the 195 articles, Figure S5: Venn diagram showing the number of documents approaching environmental, social or economic aspects or combinations of these three, Figure S6: The above figure shows the most-cited article (Li, 2005), indicated by the name of the first author, The below figure is the same figure as the first figure but without the unconnected/unlinked documents, (Newell 2013) is the most cited document by the authors of this research review, and (Li, 2005) is the most cited document by other authors outside this literature review, Figure S7: The highest number of articles is represented by one of the green circles, it belongs to Dagmar Haase.

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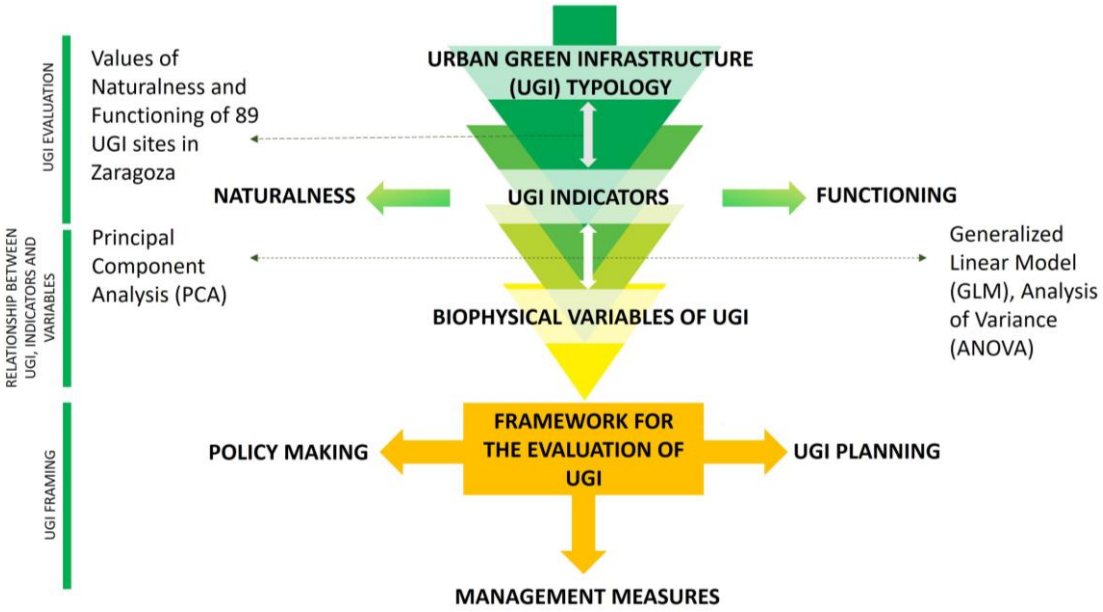

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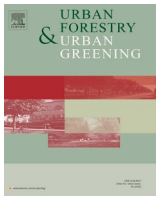

Evaluating naturalness and functioning of urban green infrastructure☆

Elie Hanna [a,b,*], Daniel Bruno [a,c], Francisco A. Comín [a]

[a] Instituto Pirenaico de Ecología, Consejo Superior de Investigaciones Científicas-CSIC, 50059 Zaragoza, Spain
[b] Department of Agricultural and Natural Environment Sciences, Higher Polytechnic School, University of Zaragoza, 22071 Huesca, Spain
[c] Department of Applied Biology, Miguel Hernández University, 03202,Elche, Spain

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ABSTRACT

Evaluating the state of urban green infrastructure (UGI) is a basic step to reach urban sustainability. Two indicators were used to evaluate 89 UGI sites in Zaragoza, a medium-sized city in NE Spain: Naturalness (Nat), related to the area covered by natural components; Functioning (Fun), related to the area showing natural hydrogeomorphological features. Complementarily, 15 biophysical and social variables were used to characterize these sites. A principal component analysis (PCA) was performed to group variables and types of UGI, while linear regressions and ANOVAs were applied to identify relationships between UGI characteristics, Nat and Fun.

The Zaragoza UGI was dominated by artificial regular sites. Most sites (73%) have low-medium values of Nat and Fun. They were mostly flat urban parks with very regular forms located in the most densely urbanized zones, and 20% of the sites have high values of Nat and Fun, corresponding to well-conserved natural areas, either unchanged or slightly transformed. Only 3 sites displayed high Nat values and low Fun values. No sites had high Fun values and low Nat values. These groups of UGI sites were mostly distributed along the first axis of the PCA which represented the natural and heterogeneous forms versus regularity and flatness features. The UGI sites scattered throughout the second axis represented a gradient from paved to vegetated sites. Both Nat and Fun were positively correlated with area, natural subsoil and the area covered by vegetation but negatively with artificial soil, regularity and flatness after the linear regressions and ANOVAs.

These results show that Nat and Fun are effective indicators to assess UGI sites. Minimizing regularity of design, preserving the natural topological relief, and restricting the area covered by artificial components are suggested to achieve a balanced representation of ecosystem processes, functions, and services within the UGI network of a city.

1. Introduction

The network of urban green zones, referred to as the urban green infrastructure (UGI), is an essential part of urban ecology, as it provides key multiple ecosystem services and certain urban resilience against climate change (Coutts and Hahn, 2015). There is a growing body of literature about the potential benefits of UGI as they perform important ecological functions for humans, such as climate change adaptation and mitigation (Pauleit et al., 2013) by ameliorating the meteorological conditions through the provision of shade, the lowering of solar radiation and the reduction of extreme temperature variations (Di Leo and Dubbeling, 2016), and subsequently by reducing energy use (Cheshmehzangi et al., 2019), among others. Properly designed UGIs can also help to manage and reduce disaster risk (Onuma and Tsuge, 2018) and boost biodiversity conservation (Hostetler et al., 2011). They also provide social and cultural benefits, such as increasing longevity (Jonker et al., 2014) and improving human health and well-being through the reduction of atmospheric pollution (Kim and Miller, 2019), the amelioration of the effects of heatwaves (Jonker et al. 2014), the promotion of mental wellness (e.g., stress relief), physical activity (Cohen et al., 2007), social communication (Cortinovis et al., 2018) and recreational opportunities (Terkenli et al., 2017), while also helping to build cultural vibrancy (Kumar and Vuilliomenet, 2021). UGI can also be considered as economic assets, as they can influence economic growth (Khoshnava et al., 2020) by increasing land and property values (Madison, n.d.) and food provision (Russo et al., 2017). The UGI physical and psychological benefits can also represent prominent economic benefits for the population (Center for Neighborhood Technology, 2010).

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* Corresponding author at: Instituto Pirenaico de Ecología, Consejo Superior de Investigaciones Científicas-CSIC, 50059 Zaragoza, Spain.
E-mail addresses: 812719@unizar.com (E. Hanna), dbrunocollados@um.es (D. Bruno), comin@ipe.csic.es (F.A. Comín).

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During the present century, an increasing scientific interest in the study of UGI, following major environmental summits has been observed (Hanna and Comín, 2021). Given that the practical implementation of semi-natural solutions to improve UGI requires an evidence-based but cost-effective valuation, it is urgent to design simple but accurate valuation tools tailored to support the development of UGI (Van Oijstaeijen et al., 2020). Simultaneously, there has been a quick implementation of the so-called green zones in cities all around the world with an increase of about 4.11% during this century (Huang et al. 2017), which contributes to raise global environmental awareness on the role of urban areas for human well-being and the sustainable development of the planet (Davies and Lafortezza, 2018). Given the disconnection between policy, management, and science (Sutherland et al., 2013), improving the design and performance of UGI based on the best scientific knowledge is becoming one of the major challenges for urban policy makers because of the tight link between green zones and inhabitants' well-being (Panagopoulos et al., 2015), given that the UGI contribute to both ecosystem and human health (Tzoulas et al. 2007). For this, it seems necessary to develop representative and easy-to-use indicators of UGI design and performance in terms of ES.

To date, a variety of types of indicators has been used to assess UGI. The European Environmental Agency (EEA 2017) proposed a series of indicators: air quality, noise, water, sustainable land use and soil, waste and circular economy, nature and biodiversity, green growth and eco-innovation, climate change mitigation and adaptation, sustainable urban mobility, energy performance, environmental governance. These indicators displayed on an interactive map aim to help cities in assessing the quality of their UGIs. Furthermore, an indicator of the effectiveness of UGIs was proposed by Fernández de Manuel et al. (2021) based on the assessment of run-off retention, air purification, and cooling. To assess how effectively these 3 environmental processes are provided by various urban terrestrial and aquatic sites, their supply and demand imbalances were examined at the neighborhood scale through geospatial and statistical analysis. Tudorie et al. (2019) classified environmental indicators of UGI according to well-established ecosystem services frameworks. Carmen et al. (2020) asked stakeholders of four medium-sized European cities about the relevance of a set of indicators covering environmental, social, and economic aspects of green sites. In general, these studies suggested that it is essential to unify indicators and create integrated indexes to reach a real management tool that help cities to develop effective urban planning.

So, there is a lack of simple but integrative tools to evaluate the state of the UGI. Using indicators of multiple characteristics is a useful approach to describe and explain a series of features, although it does not ensure a synthetic evaluation of urban green sites use to compare sites (Wendler et al. 2022). Another problem is related to the spatial scale as it is difficult to evaluate all the sites composing the green structure of an urban zone using multiple characteristics because of the complex and sophisticated equipment required (Pakzad and Osmond, 2016). In addition, many of the approaches to evaluate UGI do not use quantitative data but just descriptive features (Hanna and Comin, 2021). These three common problems combined indicate that indexes synthetizing major features would provide a simple but useful evaluation tool of UGI sites. Most of the indicators use in many studies focus on environmental characteristics but not on the key features of the UGI sites. It is urgent to design simple but accurate valuation tools tailored to support the development of UGI (Van Oijstaeijen et al., 2020).

Our approach here is based on the hypothesis that the two major descriptive features of ecosystems, structure, and function, are good indicators of the state of UGI sites. Consequently, they should be used for their evaluation, as UGI sites can be considered ecosystems. As a result, descriptors of their structure and function are essential features to be used to describe their characteristics (Rowntree, 1984; Rowntree, 1986). The UGI is usually composed of different types of green spaces and a variety of structures which contain natural (trees, shrubs, herbs, natural water springs, natural rocks etc.) and artificial components (benches, tables, recreational components, architectural structures, etc.) (Andrade et al., 2013, Borelli et al., 2015). Less natural UGI, like urban parks, green roofs and facades, street trees, pocket parks, grassland, community gardens, canals and cemeteries often contain human-made components that facilitate their use by people (Shafer et al., 2013). Other UGIs are similar to undisturbed ecosystems mostly dominated by natural components such as rivers and forests, integrated in the urban area and more or less modified to facilitate recreational uses (Cvejić et al., 2015; Kowarik, 2011).

The state and performance of UGI can be indicated through the evaluation of its structure and functions, which can help to suggest cost-effective improvements to maximize the benefits for the population (Palliwoda et al., 2020).

The objective of this paper is to evaluate the structural and functional aspects of the urban green zones of a medium size city in Spain using two ecological indicators, Naturalness (Nat) and Functioning (Fun), defined by the degree of natural components and natural processes, respectively. Subsequently, we analyzed Nat and Fun in relation to a set of attributes represented by geomorphological, vegetation, soil, and social variables. These variables were selected to cover morphological components (regularity, flatness) and ecological characteristics of the UGI (plant material and vegetation cover), as well as features connected to citizen use (circulation, weekend or weekdays use of the UGI sites, time, day/night use of the green zones). This approach allowed us to study the potential of Nat and Fun to evaluate the structural and functional characteristics of urban green zones, which is useful both to improve the characteristics of individual sites and to assess the full set of green zones of a city.

2. Methods

2.1. Study area and sampling method

The study area corresponds to the urban zone of Zaragoza municipality (Spain, coordinates 41.6488° N, 0.8891° W), a medium-sized city (734,000 inhabitants; 167 km^2) (van den Berg et al., 2017), or an XL sized city according to "Cities in Europe, The New OECD-EC Definition" (2013). Zaragoza is the capital city of Zaragoza Province (972,000 inhabitants; 17,274 km^2) and of the autonomous community of Aragon (1, 332,000 inhabitants; 47,720 km^2) (Fig. 1). The residential enlargement of the city is taking place mainly in its North and South poles, with a few neighborhoods recently urbanized and others in the process of urbanization.

Zaragoza city (249 m above sea level) is located in the north-east of the Iberian Peninsula, in the middle of the valley of the Ebro River (average water discharge 230 m^3/s, with ordinary floods of 1200 m^3/s and extra-ordinary floods up to 2800 m^3/s; Ruiz-Bellet et al. 2015), a river which crosses the city in a northwest-southeast direction, receiving two tributaries (Huerva and Gallego) in the city. Zaragoza has a semi-arid Mediterranean climate. The average annual precipitation is 322 millimeters, and the rainiest seasons are spring (April–May) and autumn (September–November), with a relative drought in summer (July–August) and winter (December–March). It is characterized by high isolation and relatively extreme temperatures: hot in the summer reaching up to 44.5 °C and cool in the winter reaching < 0ºC (-2 ºC as minimum temperature). A cold and dry wind from the northwest blows frequently in the winter. During non-windy days of autumn-winter, fogs are frequent. The surroundings of the urban zone of Zaragoza are a typical steppe habitat with about 50% of shrub cover over gypsum soils (Comín et al., 2005).

During the last centuries, the Ebro River was transformed into a rectilinear stretch in Zaragoza city, but it maintains large floodplains upstream and downstream (Ollero-Ojeda et al., 2006). The Gállego River, one of the main tributaries, still preserves large floodplains in Zaragoza city and upstream. The other tributary, the Huerva River, is fully channelized and flows mostly underground. Apart from the

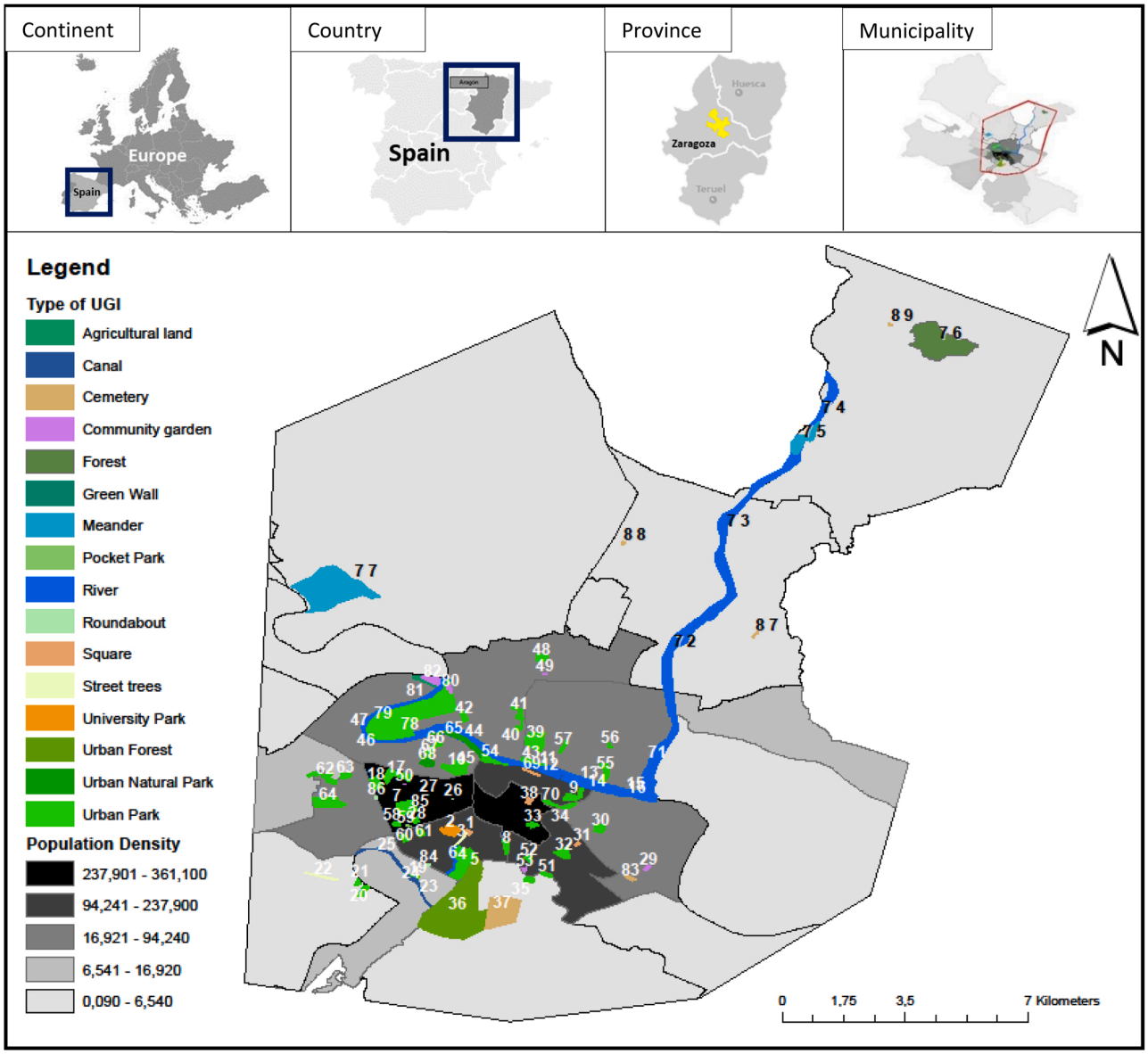

Fig. 1. Study area corresponding to the municipality of Zaragoza (Spain). This map shows the typology of the UGI elements that we visited and evaluated in relation with the population density of the city. (Check Fig. S1 in the Supplementary Materials for a zoom in on the city)

waterways, there are large natural green zones next to the city such as an oxbow lake and its floodplain (Galacho de Juslibol, 1.22 km^2), an abandoned meander of the Ebro River upstream but next to the city, and the steppe zone (332 km^2) in the southern part.

The UGIs of Zaragoza consist of natural, semi-natural, and artificially constructed sites, encompassing terrestrial and aquatic ecosystems. Some of them are small sites located in the most densely urbanized zone of the city whereas relatively large green spaces (river banks, forests, meanders) are mostly located in the peri-urban surroundings of the city.

Artificially constructed sites located in the urban area are relatively small UGIs: community gardens, urban parks, urban natural parks, pocket parks, green walls, cemeteries, squares, roundabouts, university parks, community gardens, irrigation canals, roundabouts, and street trees (note that this typology was developed by the European Commission, https://biodiversity.europa.eu based on Cvejić et al., 2015).

In this study, 89 UGI sites (Table S1) were visited and evaluated, 80 of them located within the city (urban parks, urban natural parks, university parks and urban forests, representing 81.7% of the total area of green zones in the city) and 9 in semi-urban zones on its periphery (Fig. 1). Environmental data were collected in-situ, from municipality data, observation and satellite imagery, encompassing 15 variables to characterize the degree of naturalness and artificiality and to detect the effects of natural dynamics (erosion, fire, strong wind, accumulation of organic matter, soil formation) in each UGI site. The set of UGI studied included community gardens, urban parks, pocket parks, green walls, squares, roundabouts, urban natural parks, university parks, urban forests, community gardens, irrigation canals, roundabouts, street trees, river banks, forests, cemeteries, rivers, meanders, and agricultural fields. Given that a few UGI sites (Parque Grande José Antonio Labordeta, Parque del Agua, the Ebro River banks, River Gallego) cover a large area and encompass a high spatial heterogeneity, they were divided into homogeneous zones according to their location, topography, and degree of artificiality. For instance, Parque del Agua (124.3 ha) encompasses a high spatial heterogeneity; it has a natural part with well-conserved native riparian ecosystems (human intervention is limited) (area = 45.1 (ha)) and an artificially designed part (area = 79.2 (ha)). Hence, it was divided into 2 units and each unit was evaluated separately.

2.2. Evaluation of the UGI sites

The overall approach used here to evaluate UGI sites aims to quantify their structural and functional characteristics through two complementary indicators called naturalness (Nat) and functioning (Fun) (Fig. 2). Nat indicates the degree of natural versus artificial components forming the UGI site. Similarly, Fun indicates the degree of natural versus artificial processes driving the functions of the UGI site. The methodological steps followed in this study can be seen in Fig. 2.

Additionally, 15 variables were selected to describe physical (area, flatness, regularity, artificial soil, natural subsoil), ecological (vegetated area, bare soil, native vegetation, artificial plantations, number of vegetation strata, plant pots and grouping), and social (circulation, daytime and weekend use) characteristics of the UGI sites (Table 1). Regularity, flatness, area, artificial soil, natural subsoil, bare soil, and vegetated area were estimated through Google Earth and ArcGIS (Vector) and calculations (formulas). We used the imagery available in Google Earth with a resolution less than 1 m/pixel and the imagery available in ESRI Basemap available in ArcGIS with a resolution less than 1 m/pixel. The imagery of Google Earth is from Maxar High Resolution Satellite Imagery. The imagery of ArcMap is from National Area Orthophotography Plan from National Geographic Institute (PNOA-IGN). Native vegetation, artificial plantations, number of vegetation strata, circulation, plant pots, and grouping through direct in-situ observations; daytime and weekend use through a combination of surveys performed weekly during peak-used periods; May, June and July 2020, by counting park users 3 times per day at three-hour intervals for a minimum of 3 days a week including two weekdays and one weekend day, also we used municipality data. These variables were correlated with Nat and Fun indicators to discriminate which were the variables most closely related to the two indicators and which groups of UGI sites can be distinguished. Area of the site with artificial soil or planted vegetation, the existence or not of plant pots, and plant groupings are related to their degree of naturalness and were used to describe the structure of UGIs. Other variables are related to functional aspects: how much of the UGI is occupied by regular forms or by flattened soil. More regular flat forms indicate a strong anthropogenic modification that control the site. In contrast, the dominance of irregular forms and irregular distribution of dead and decomposing organic matter, combined with sings of water and wind flows indicate that natural drivers regulate the functioning (e.g., active and/or natural geomorphology, primary production, soil formation). The remaining variables are related to social aspects (how much the site is used by people during work days or weekends, and how accessible it is for circulation) which are also linked to the anthropogenic influence. Daily used sites are more artificially managed in order to facilitate people's use, while sites used principally during weekends tend to be more natural and well-conserved.

Nat was measured as the percentage of coverage of natural areas inside the UGI site. Natural areas can be covered or not by vegetation (there may be zones without vegetation, naked soil or rocks naturally established). Artificial areas are those established or built by humans, including planted vegetation, recreation, and service facilities, but not pedestrian or cycling routes through natural areas. Nat evaluation was done through fieldwork (UGIs in-situ characterization), visualization, and analyzing satellite images (Google Earth and ArcGIS). A similar scale to that of Machado (2004) was used to assign Nat values to each UGI site evaluated. A grading system ranking from completely natural (10) to completely artificial (0) sites was established (Table S2). A set of descriptive conditions defined each value; some of these conditions are optional. For example, to reach a Nat value of 1, a site can have 90–100% of the area occupied by artificial components, but built and ornamental structures not necessarily present. Decimal values were assigned accordingly. For example 3.4 means that only 34% of the site area, was covered by natural components. Therefore, Nat= (% of the area with natural components)/10.

An analogous scale was established to assign values for Fun, which was defined as the degree of natural processes driving the dynamics of the UGI site based on the classical concept of ecosystem functioning (Bürgi et al., 2004; Tiegs et al. 2019). It was measured as the area of the UGI site observed with natural dynamic features according to Table S3. These features were identified as signs of hydro-geomorphological drivers (wind and water flows, flooding, and erosion) and biological processes (organic matter accumulation) observed in the UGI sites. Marks and traces of wind and water flows can be identified easily in an ecosystem as dragged soil, bent trees, and organic matter which form irregular paths. Artificial processes used to shape regular accumulations of soil and paths. In a similar way, fallen herbs, leaves, branches and trunks are usually accumulated temporarily in more natural spots or removed from more artificial ones. The values of Fun ranged from 0 to 10, with 0 indicating non-functional sites highly influenced by humans,

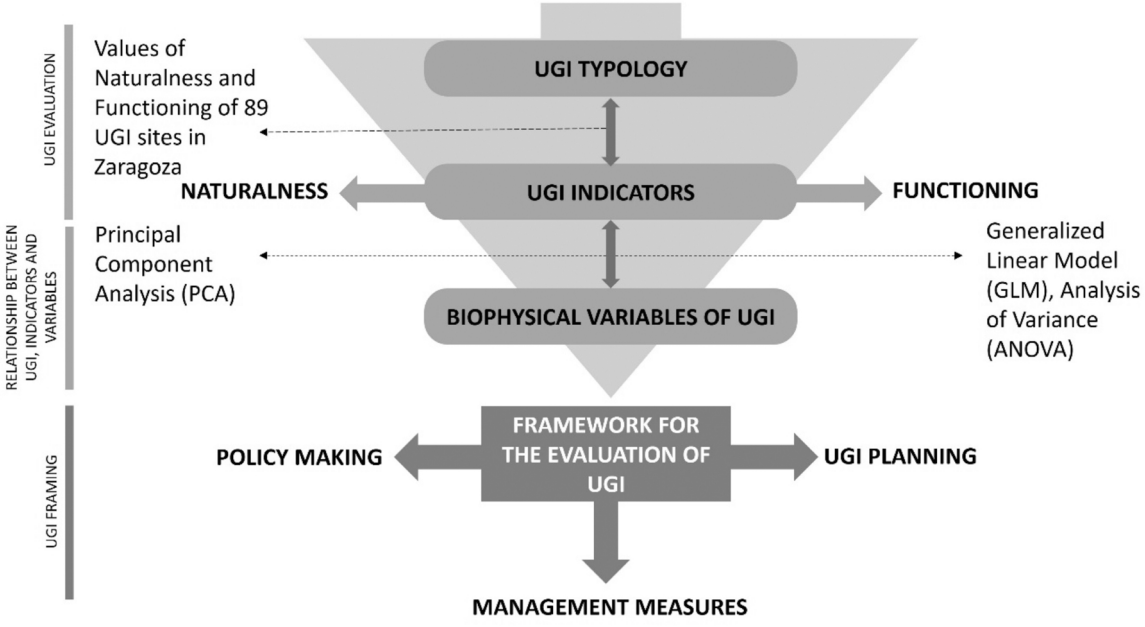

Fig. 2. Diagram illustrating the different steps followed in the methodology of this study.

Table 1
Type, definition and methodology of the 15 variables used to assess the UGI of Zaragoza (For more details, please check Table S4).

Type of Variables	Definition	Methodology	Formula
Regularity	It's the extent to which a site is designed using strict lines or well defined regular forms. For instance, a landscape designed park, containing symmetrical design and well defined shapes (strict lines of trees, round fountains, lines of pavement) in its design might have a value of 4 or 5 (depending on how artificial the park looks). On other hand, a natural forest is not artificially designed (because it is natural) have a value of 1 since strict lines of trees with equal spacing for example are rarely found in nature.	ArcGIS data; it is obtained by drawing a Polygon around the area of artificial design (with strict line or/and regular shapes), obtaining its area and dividing it by the total area of UGI	(Area of artificial design/Total area of the site) × 100
Daytime	The day and night use of the site	Survey and Municipality data	None
Weekend_Use	The weekday vs. weekend use of the site	Survey and Municipality data	None
Area	Total area of the site	Google Earth and ArcGIS data; it is calculated by drawing a Polygon around the UGI element and obtaining its area.	(Area of artificial components) + (Vegetation Area) + (Area of natural soil that is not covered by vegetation)
Artif_soil	Area of the site that is occupied by artificial components such as pavements, structure, fountains, houses, sport playgrounds etc.	ArcGIS data; it is calculated by drawing Polygons around the artificial zones inside the UGI element. Then obtaining the areas of the artificial zones (using Calculate Geometry inside the attribute table in ArcGIS). We added up the areas of the Polygons to obtain the total artificial area in the UGI element. Also it can be obtained with a formula.	(Area of the site) – (Vegetation Area) – (Area of natural soil that is not covered by vegetation)
Vegetation_Area	How much area is covered by vegetation	ArcGIS data; it is calculated by drawing Polygons around the vegetated zones inside the UGI element. Then obtaining the areas of the vegetated zones (using Calculate Geometry inside the attribute table in ArcGIS). We added up the areas of the Polygons to obtain the total vegetation area in the UGI element. Also it can be obtained with a formula.	(Area of the site) – (Area of artificial components) – (Area of natural soil that is not covered by vegetation)
Natural_Soil_No_Vegetation	The natural area of the site that is not covered by vegetation	ArcGIS data; it is calculated by drawing Polygons around the natural zones inside the UGI element that is not covered by vegetation. Then obtaining the areas of the zones (using Calculate Geometry inside the attribute table). We added up the areas of the Polygons to obtain the total natural area inside the UGI element that is not covered by vegetation. Also it can be obtained with a formula	(Area of the site) – (Area of artificial components) – (Vegetation Area)
Natural_Subsoil_Area	% of the total area of the site that is occupied by natural subsoil	ArcGIS data, Google Earth and observation. It is important to note that we did not measure the depth of natural	(Natural area/ Total area of the site) x 100

(continued on next page)

Table 1 (*continued*)

Type of Variables	Definition	Methodology	Formula
		subsoil. We are talking about the presence of natural subsoil and the% of area natural subsoil is present in the site. Thus, natural subsoil depends on the presence of natural area (vegetated + non vegetated area), for instance, a site that is occupied 100% by natural area (a natural forest for example) will have natural subsoil area= 100% because 100% of the total area of the site is occupied by natural undisturbed subsoil (no anthropogenic impact). On the other hand, low % of natural subsoil is found in designed UGI sites, such as artificially designed parks and street trees. The% of natural subsoil area is calculated by dividing the% of the natural subsoil area of the site (vegetated and non-vegetated) by the total area of site.	
Flatness	% of flatness in the sites	ArcGIS data, Google Earth and observation. It was calculated by drawing a Polygon around the flat zone, obtaining its area and dividing it by the total area of the UGI element.	(Area of the flat zone/Total area of the site) × 100
Nat_veg_plant	The existence or not of natural plantations	On site observation	None
Artif_planted	The existence or not of artificial plantations	On site observation	None
Plant_pots	The existence or not of plant pots	On site observation	None
Plant_group	The existence or not of plant grouping	On site observation	None
Veg_Strata	Number of strata in vegetation	On site observation	None
Circulation	How much the site is easily accessible and navigable	On site observation	None

and 10 pointing to complete preservation of natural hydro-geomorphological features and processes, and that artificial traits of anthropogenic processes were completely absent. For example, a value of 6.7, means that 67% of the total area of the site maintains its hydro-geomorphological and biological related features. Therefore, Fun= (% of the area with natural hydro-geomorphological features)/10.

2.3. Ordination of UGI sites based on their physical, ecological, and social features and their relationships with Nat and Fun indicators

A multivariate analysis was conducted to assess the characteristics of the UGI sites. In particular, UGI sites were ordered and grouped in a multidimensional space according to their socioecological features (15 variables) (Table 1), using a principal component analysis (PCA) followed by an agglomerative hierarchical clustering (Ward's criterion) and partitioning clustering (k-means algorithm to improve the initial partition obtained from hierarchical clustering) to automatically identify the optimum grouping of sites according to their shared environmental features (FactoMineR R package; Husson et al., 2014). Complementarily, individual linear regressions were performed to detect which variables were driving the variability of Nat and Fun. Similarly, ANOVAs, equivalent to linear regressions, were performed on categorical and binary variables. An automated selection procedure on General Linear Models (GLM) was performed to detect the best combination of variables to explain the Nat and Fun patterns based on small-sample corrected Akaike Information Criterion (AICc; best-fitting models were those with lower AICc and greater goodness of fit-R^2). Homoscedasticity and normality of residuals were checked visually. Prior to analysis, the variables "Area" and "Artif_soil" (Table S4) were log-transformed when necessary, to reduce skewness in the distribution of the explanatory variables. All quantitative predictors were Z-standardised (mean = 0, SD = 1) before PCA and GLMs, to allow for model coefficient comparison. The variance inflation factor (VIF=$1/(1- R^2)$) was calculated to check predictor collinearity (Zuur et al., 2010) and to remove excessively correlated variables ($r > 0.7$) prior to GLM.

All analyses were conducted in R (R Core Team, 2020) using the packages *glmulti* (Calcagno and Mazancourt, 2010), *ggplot2* (Wickham, 2011), and *FactoMineR* (Lê et al., 2008).

3. Results

3.1. Naturalness (Nat) & Functioning (Fun) of UGI sites

Most of the UGI units of Zaragoza, 65 out of 89 (73%), were characterized by low values (<5) of Nat and Fun (Fig. 3). Two of these sites were found to be extremely artificial, showing Nat and Fun values near 0. One of the sites is a (2 ha) square in downtown that was completely covered with artificial components, except for scattered small plant pots garnishing a few sitting benches; the other one is a cemetery (0.65 ha), also covered by artificial soil, except for isolated planted trees. The other

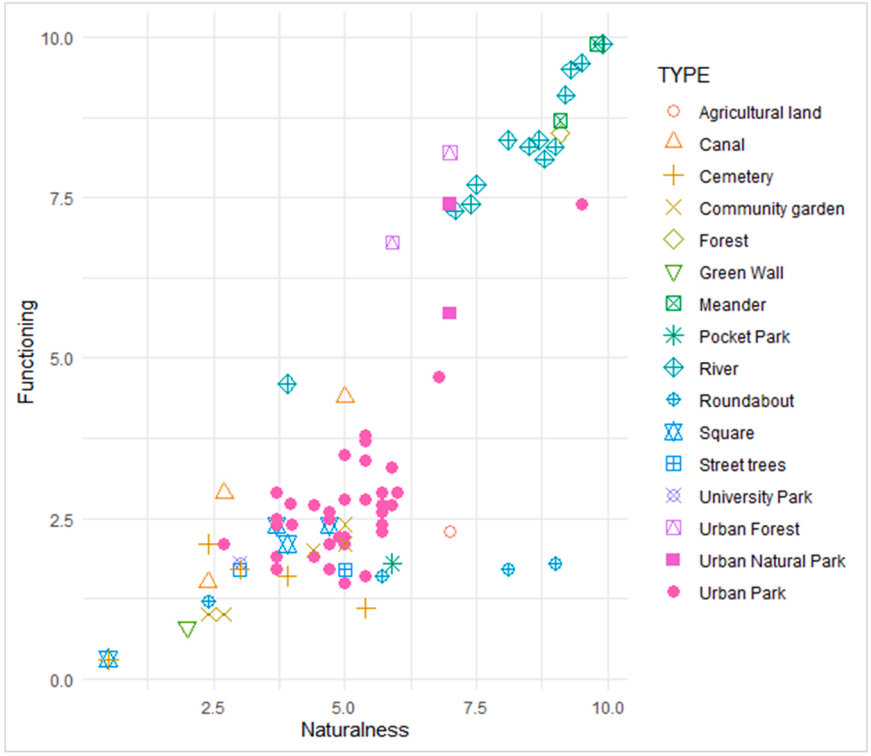

Fig. 3. Values of Functioning and Naturalness of 89 UGI sites in Zaragoza. Each symbol represents an UGI element.

sites of this group of low Nat and Fun values included a wide range of UGIs such as urban parks, university parks and squares, with a high proportion of artificial cover and, usually, planted flower pots or beds, combined with impervious surfaces, facilities for citizens' enjoyment (children's playgrounds, bar and restaurant terraces), and/or underground infrastructures (multi-story car park, petrol station). This group of UGIs also included community gardens which consisted of small urban agricultural lots with rest rooms, barbecue zones, and storehouses to stock agricultural items, as well as cemeteries (there are 9 cemeteries in the urban zone, this study evaluated 5 of them), human-made canals, and a small urban river area (Rio Huerva inside Parque Grande) with a low-medium value of Nat (3.9) and Fun (4.6) because its riparian area is very narrow and displayed a poor conservation status.

A group of UGI sites showed Nat values between 5 and 6, but low values of Fun, ranging between 1 and 4.6. These sites mostly represented urban parks and street trees (road alignment) with regular plantations of trees that maintain some natural components combined with aboveground artificial facilities for recreation and public enjoyment. The biggest cemetery in Zaragoza (51 ha), which was characterized by rows of trees on the sides of pathways, graveyards and architectural structures, also fell within this group.

Another group comprised 20% of the UGI sites (18 of them), characterized by high Nat and Fun values (>7) was dominated by natural sites that included rivers and riparian areas and forests, meanders, and a large urban forest (Pinares de Venecia, 318 ha). These sites displayed artificial components used for recreation, but their effect on Nat & Fun was minimal compared to the influence of existing natural components.

Three urban parks displayed intermediate values of Nat and Fun (4.7–7). They were characterized by artificial components (e.g. bar terraces, fountains, compacts walks, pedestrian boulevards), but maintaining key natural features such as the original topography and autochthonous vegetation (mostly planted).

Another three sites showed a high Nat (7–9) but a low Fun value (about 2), which corresponded to an urban agricultural land (82) and two roundabouts (85, 86) with a dominance of natural but ornamental components where natural dynamics were depleted. Roundabouts can have high Nat values since they are covered by lawn and plantation. However, they are artificially constructed so their Fun value was very low due to the lack of preservation of any hydro-geomorphological aspect (the presence of natural dynamics is negligible).

We did not find any UGI site with opposing extreme values of Nat (< 5) and Fun (> 5), which seems quite logical since high Fun values are driven by natural dynamics, and hence, should have also high Nat values.

3.2. *Grouping Urban Green Infrastructure sites*

The two first axes of the PCA analysis accumulated 47% of the data variability. A high difference between the 36.6% of the Principal Component (PC) 1 and the 10.7% of the PC2 was observed. The next PC represented less than 10% each of the remaining data variability (Table S5). Accordingly, we retained the two principal axes for interpretation of data variability.

Variables "Area", "Natural_Soil_No_Vegetation", "Natural_Subsoil_Area", "Vegetation_Area", "Daytime" or "Weekend_Use", "Nat_veg_plant","Naturalness", "Veg_ Strata" and "Functioning" were positively correlated with the PC1, while variables "Flatness", "Regularity", "Artif_soil" and "Plant_pots" were negatively correlated (Fig. 4a). The distribution of the UGI sites along the PC1 represented a gradient from natural to artificial. Three automated major clusters of UGI sites were detected (Fig. 4b). Cluster 1 was made of sites representative of river, meander and urban forest. Cluster 2 was mostly composed of urban parks. Cluster 3 contained highly artificially designed UGI sites as community gardens, cemeteries, squares and street trees.

The distribution of sites along PC2 represented a gradient from constructed and artificial UGI sites characterized by intense paving to more vegetated but architecturally designed UGI sites. Variables positively correlated with PC2 were "Circulation", "Artif_planted" and "Plant_ group", whereas "Weekend_Use" and "Natural_Soil_No_Vegetation" were negatively correlated (Fig. 4a). All the UGI sites distributed along this PC2 axis were in the negative side of PC1 axis since they corresponded to very regular shapes with artificial soil. UGI

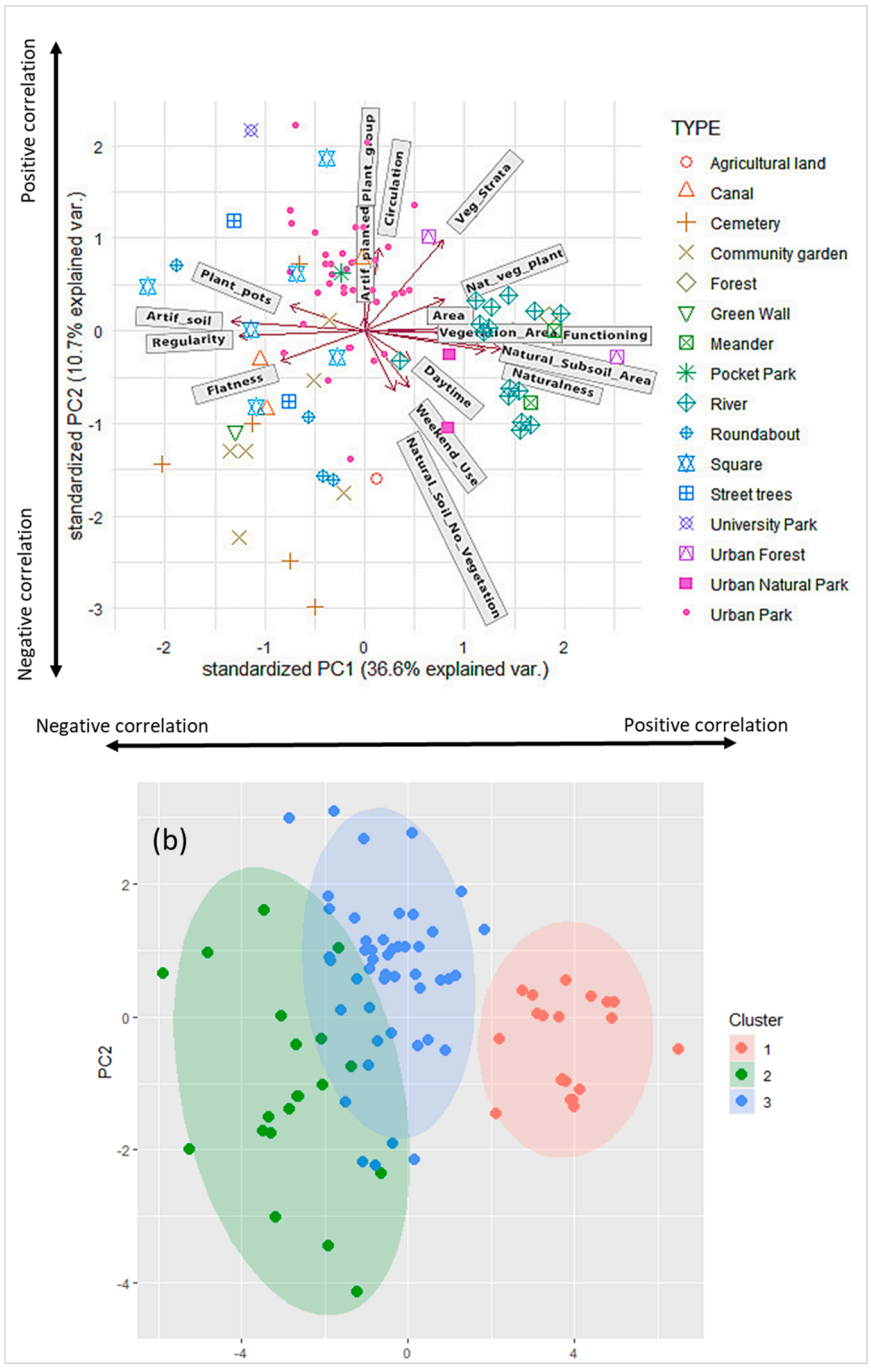

Fig. 4. (a): PCA ordination of UGI sites and variables studied in relation with the two first axes of variability. Each symbol represents an UGI element. "Nat" is the abbreviation of Natural, "Artif" is the abbreviation of Artificial, and "Veg" is the abbreviation of Vegetation. (b): Hierarchical clustering according to the shared features of UGI elements.

sites covered by artificially planted vegetation and other artificial components (e.g. sites number 2, 3 and 26 in Table S1) occupied the positive part of the PC2 axis while those flat units with regular shape (e.g. site number 53, 88 and 89 in Table S1), were distributed along the negative part of PC2.

3.3. Relationships between Naturalness and Functioning indicators and characteristics of UGI sites

Individual linear regressions showed that all explanatory variables resulted in highly significant Nat and Fun distribution patterns ($p < 0.001$ in all cases). Both, Nat and Fun indicators were positively related to "Natural_Subsoil_Area", "Area", "Vegetation_Area", "Veg_Strata" and Nat_veg_plant, but negatively related to "Artif_soil", Regularity, "Plant_pots" and "Flatness" (Fig. 5, Table 2). However, they differed in the amount of explained variance (goodness of fit -R^2). Nat was highly negatively related to "Artif_soil" (c in Table 2 and Fig. 5; $R^2 = 0.92$), and "Regularity" (g, $R^2 = 0.44$), but positively to "Area" (a; $R^2 = 0.44$).

Similarly, "Artif_soil" (l) showed the strongest negative relationship with Fun ($R^2 = 0.7271$). However, compared to Nat, Fun displayed a stronger negative relationship with "Regularity" (p) ($R^2 = 0.6996$), followed by a positive relationship with "Natural_Subsoil_Area" (o) ($R^2 = 0.663$) and "Area" (j) ($R^2 = 0.595$). "Vegetation_Area" was excluded

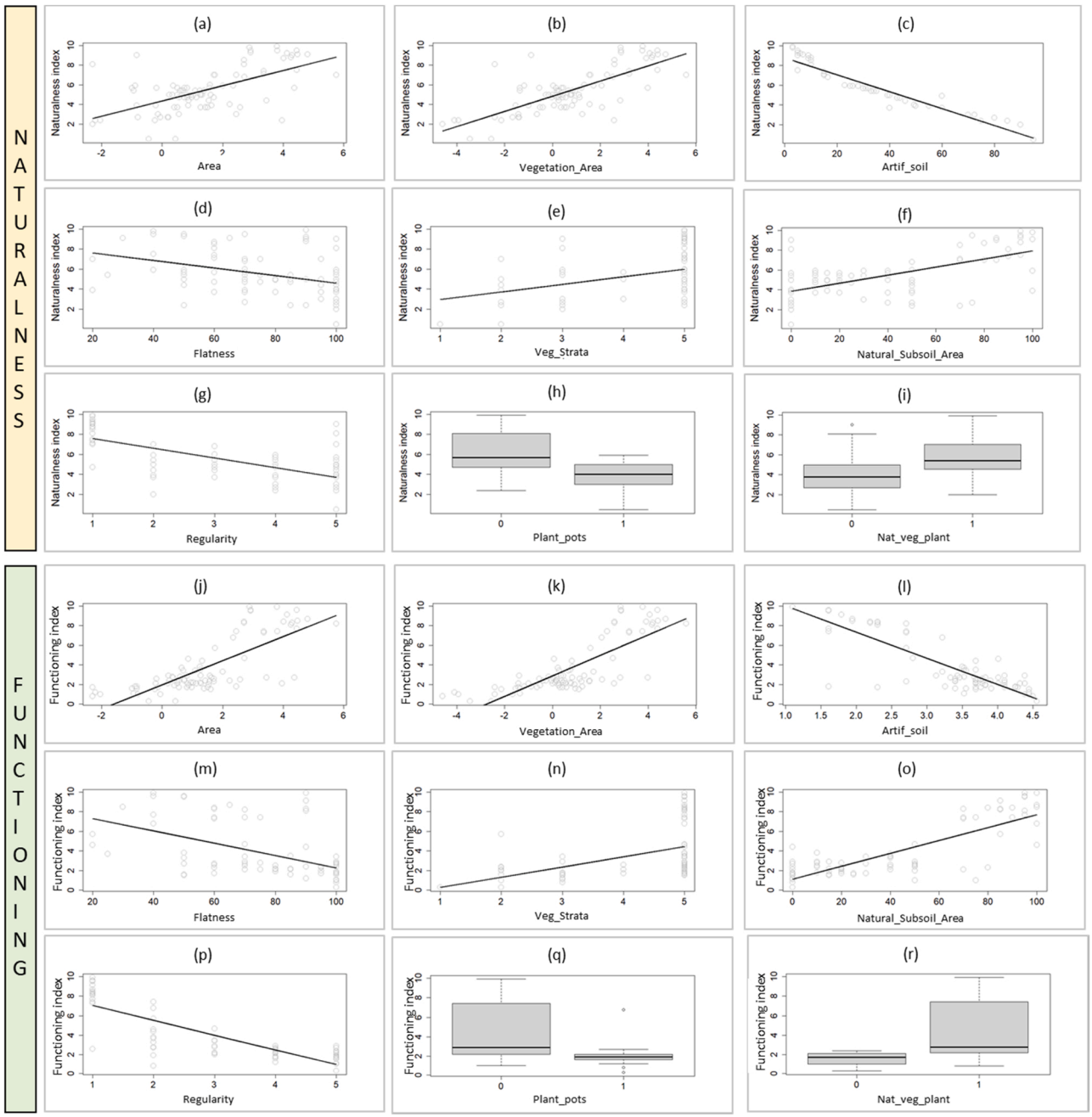

Fig. 5. Linear regression plots showing significant (p-value < 0.05) relationships between individual variables and Nat and Fun. Equivalent ANOVAs were performed for binary variables (h), (i), (q), (r), which were represented by boxplots (the median is denoted by the bold horizontal line, the box delimits the interquartile range, and the whisker lines extend to the observed maxima and minima, except for the outliers symbolized by points).

from the analysis to avoid multicollinearity, given the high correlation ($r = 0.98$) found between this variable and "Area".

Regarding the best combination of variables explaining Nat patterns, we found that the best-fitting model (R^2 =0.92) included "Artif_soil" and "Regularity". However, the improvement in terms of explained variance is marginal in relation to that provided by the model just including "Artif_soil" (R^2 =0.9164). The best-fitting model for Fun included "Regularity", "Area", and "Artif_soil" (R^2 =0.89), improving substantially those resulting from individual regressions (Table 3).

4. Discussion

4.1. Characterization of UGI in the city of Zaragoza

The results of this study indicate that the UGI sites of Zaragoza city were distributed throughout the Nat & Fun combined range. UGIs of Zaragoza city were mainly characterized by low-medium values of Nat and low values of Fun, which corresponded to highly artificial UGIs with very regular shape and flat surface, located in the most densely urbanized zones of the city. Only 20% of the studied sites displayed high values of Nat and Fun, which corresponded to well-conserved natural areas (e.g. floodplains, hills), either unchanged (those located in the suburbs) or slightly transformed (surrounded by the urbanized parts of the city).

Table 2
Generalized Linear Model (GLM) summary of Naturalness (Nat) and Functioning (Fun) indicators with environmental variables representing major characteristics of urban green zones in Zaragoza city.

Indicator	Model	Variables	Adjusted R Square	Estimate	Std Error of the Estimate	p-value
Naturalness	(a)	Area	0.3662	0.7746	0.1076	2,022E-10
	(c)	Artif_soil	0.9164	-0.085416	0.002748	2,2E-16
	(d)	Flatness	0.1306	-0.03776	0.01001	0.0002952
	(e)	Veg_strata	0.1407	0.7579	0.1931	0.0001726
	(f)	Natural_Subsoil_Area	0.3927	0.040698	0.005348	3,054E-11
	(g)	Regularity	0.4383	-0.9709	0.1163	9,759E-13
	(h)	Plant_pots	0.1989	-2,2992	0.4810	7,062E-06
	(i)	Nat_veg_plant	0.1016	1,8369	0.5551	0.001363
Functioning	(J)	Area	0.595	1,2286	0.1076	2.2E-16
	(l)	Artif_soil	0.7271	-2,6626	0.1735	2.2E-16
	(m)	Flatness	0.2401	-0.06287	0.01171	6,568E-07
	(n)	Veg_strata	0.1737	1,0463	0.2370	2,887E-05
	(o)	Natural_Subsoil_Area	0.663	0.065802	0.004986	2.2E-16
	(p)	Regularity	0.6996	-1,5280	0.1065	2.2E-16
	(q)	Plant_pots	0.1337	-2,3901	0.6260	0.0002517
	(r)	Nat_veg_plant	0.1519	2,7641	0.6751	9,443E-05

Table 3
Results of mixed-effect models showing the best-fitting model equation, P-values (significant coefficients in bold type). *(R), "Regularity"; (A), "Area"; (As) "Artif_soil"; ns, non-significant coefficient.*

Indicator	Model Equation	(R)	(A)	(As)	R^2
Naturalness	y = −0.26 R – 0.96AS	**0.00276**	ns	**< 2e-16**	0.92
Functioning	y = −1.04 R + 0.71 A −1.24AS	**1.64e-10**	**1.06e-06**	**8.99e-14**	0.89

Our approach based on Nat and Fun indicators encompassed the essential characteristics of ecosystems. Both Nat and Fun indicators were positively related to "Natural_Subsoil_Area", "Area", "Vegetated_Area", "Veg_Strata", and "Natural_veg_plant", but negatively related to "Artif_soil", "Regularity", "Plant_pots", and "Flatness" (Fig. 5, Table 2). We found a strong divergence in physical and social attributes between different types of UGIs (Fig. 4a) but a great convergence within the sites shaping them (Fig. 4b). Thus, UGI related to rivers and urban forests showed a greater size, more vegetation, undisturbed soils, naturalness and functioning than urban parks, and especially, compared to community gardens, squares, street trees and cemeteries, which were located in flat areas with artificial soil and vegetation and characterized by regular plantations with scattered trees and a reduced number of plant species.

The values of the Nat and Fun indicators were highly related between them, as shown in Fig. 3 and 4, which seem logical given that Fun could be considered as the ecological driver and Nat as an indicator of the components resulting from these functional drivers. Fully functional UGI sites seem incompatible with the absence of natural components; consequently, there were no UGI sites with high Fun values and low Nat values (Fig. 3). Conversely, the presence of natural components did not necessarily imply a high degree of functionality (e.g., UGI with a total absence of hydro-geomorphological functions but covered by planted vegetation).

Therefore, a city may have UGI sites highly regulated by hydro-geomorphological and other ecological drivers, including nutrient cycling via organic production and detritus decomposition (high Fun), which will facilitate the colonization and growth of natural vegetation (high Nat) and increase ecological resilience. However, they may be also artificially-regulated UGIs (Fig. 6), dominated by artificial components (low Nat) including recreational facilities, which will not be subjected to natural functioning processes (low Fun). In between, the city may have artificially-boosted UGI sites with a high cover of natural components (high Nat values due to the presence of several plant strata distributed more or less irregularly in mounds and hillocks), but not as the result of natural ecological processes (low Fun). Overall, a city cannot have long-lasting UGIs driven by natural processes (high Fun) with low cover of natural components (low Nat) because the drivers regulating the ecological functioning of the site would facilitate the colonization and development of plant populations and soil communities (ecologically-restricted UGIs, Fig. 6). However, there may be sites in transition states which temporarily present discordant (opposite) values of Nat and Fun. The framework defined by Nat and Fun can have a great potential for recurrent evaluations of UGI and monitor changes in their respective states (Fig. 6).

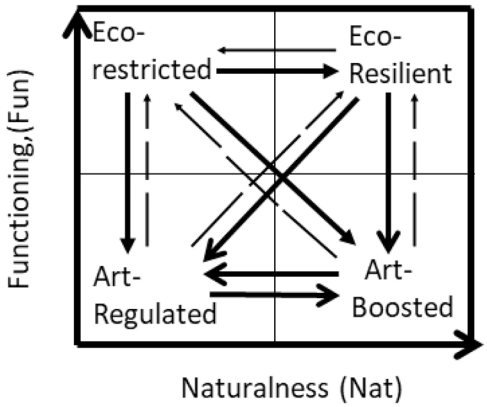

Fig. 6. Conceptual framework of alternative states of Naturalness (Nat) and Functioning (Fun) for UGI sites. The four squares in the figure correspond to UGI sites with either: high Nat and Fun (Eco-Resilient sites); high Nat and low Fun (Artificially boosted sites); high Fun and low Nat (Eco-Driven sites); low Nat and Fun (Artificially regulated sites); high Fun and low Nat (Eco-Restricted sites). The arrows show easily feasible changes of UGI sites characteristics (thick arrows) and difficult changes (thin arrows), and unlikely changes (broken lines).

Different trajectories of changes of Nat and Fun for an UGI site can be identified in accordance with the services it provides. In Zaragoza city, most UGIs (45 out of 89) displayed low to moderate values of Nat and Fun. The dominance of this type of UGI is common in densely populated cities or in highly urbanized ones, as they are designed and constructed to provide mainly cultural services (O'Brien et al., 2017; Cheng et al., 2021), leading to the dominance of artificial components, and thus, lowering the values of naturalness and functioning (Lundholm, 2015).

4.2. Urban management and planning implications

Based on our results, we propose suggestions to be taken into

consideration before, during, or after the planning of UGI in the city, at broader (city scale) and fine (UGI site) scale.

We detected a clear pattern in UGI features in concordance with that obtained for other cities worldwide (e.g., Rome, Capotorti et al. 2017) to be considered in urban planning: there is a clear separation between a group of natural sites located in suburban zones with an irregular distribution of plantations and tightly connected to hydro-geomorphological drivers as river flows, and most artificial UGIs in the most densely urbanized parts of the city, including new neighborhoods characterized by a very regular design and low functionality. This spatial segregation could be the cause of ecosystem disservices, such as biodiversity declines, given that the excessive aggrupation of very artificial sites and fragmentation of more natural remnants and UGIs can act as sink habitats (Lepczyk et al., 2017). Extreme clustering can also create a disharmony on biodiversity distribution between the UGIs sited downtown and those located in the surroundings of a city (Bötsch et al., 2018). Accordingly, it is advisable to keep natural remnants, which are still driven by ecological processes as UGI sites while a city enlarges (Snyman - Van der Walt et al., 2014), and to consider newly-built UGI as a useful tool to restore degraded zones and recover natural dynamics linked to hydro-geomorphological processes (Klaus and Kiehl, 2021). This strategy could contribute to a balanced provision of a full set of complementary ES at urban landscape scale. For example, the integration and conservation of riparian floodplains and forests in the urban landscape, as a population and city grow, can contribute substantially to the supply of ES and city's sustainability (Riis et al., 2020).

In this study, we covered most of the types of UGI elements referred to by Cvejić et al. (2015) and Kowarik (2011). Urban parks were the most common UGI type found in Zaragoza (in our case, 39 sites of 89), which seems logical, given that they are places of solace, recreation, and community fun in a stressful environment (Dunnett et al., 2002). Other types of UGI were barely present in the city; for instance, we found only one unit of green wall, even though green walls can create beneficial microclimates (buffering temperatures and increasing air humidity) and provide other environmental, social, and economic benefits such as regulating humidity, sound insulation, reducing heating and air conditioning expenses (Strumillo, 2021). We recommend urban planners to increase the type and variety of UGI, which would provide urban dwellers with a wider set of highly valuable ES that are especially affected by the reduction of diversity and surface of green infrastructure (Calderón-Contreras and Quiroz-Rosas, 2017).

The location of the majority of UGI units with high Nat and Fun values in peri-urban zones (Fig. 3), instead of in heavily populated neighborhoods, may indicate that the original geomorphology was not properly preserved during the expansion of the urban area. Thus, the land relief was changed, lowering the effect that ecological drivers can have on these UGI units. It is suggested to preserve the morphology of UGI sites incorporated to urban areas, or even imitate natural features if they are newly designed. Also, in the case of plantations, it is advised to have irregular groupings of trees and plants strategically disposed to enhance ecological connectivity, instead of scattered and isolated trees and plants without spatial continuity. Connectivity inside the site can be done using a gradual height plantation of indigenous trees and plants. The design of urban parks could be irregular, imitating in some way the English style of gardens and parks, and avoiding an excessively regular distribution of natural components (Allain & Christiany, 2006).

Furthermore, the strong negative relationship between "Artif_soil" and "Regularity" of the UGI units and the Nat and Fun indicators confirm i) the high potential of these variables to act as indicators of UGI performance, and ii) the idea that decreasing the area of artificial components and minimizing regular shapes in UGI design would favor functional processes and naturalness. Thus, we recommend the use of irregular shapes, asymmetrical distribution of vegetation, and mimicking nature in the arrangement of trees. The design should start with vegetation as the primary component and then specifying the artificial components in a way that do not disrupt the internal connectivity of plantations. Implementing these suggestions would increase the naturalness of UGIs while maintaining multifunctionality. However, improving the functional aspects of UGI sites requires keeping or recovering the influence of ecological drivers on the regulation of natural (hydro-geomorphological) dynamics (Mosler and Hobson, 2021). This may require both a broad consensus to design policies to obtain multiple ES from the set of UGI sites of a city and their systematic monitoring and assessment to ensure the accomplishment of the planned objectives. For this last purpose, the Nat & Fun indicators can be an efficient tool.

To achieve more natural and functional UGI, a shift in the mindset of decision makers and urban planners, as well as more ecological background and training in restoration ecology and environmental management, is required in their design. Up to date, UGI designers and planners have shown limited capacity to apply ecological principles to their work. The main professions involved in UGI design are landscape architecture, civil engineering, urban planning and design, with extensive involvement from lawyers, developers, and public officials. Nevertheless, environmental health and ecological processes have traditionally been omitted or marginalized by these disciplines, leading to negative impacts on urban economy and human well-being (Steiner et al., 2013).

4.3. Advantages and drawbacks of the Nat and Fun approach

Hanna and Comin (2021) performed a literature search to review types of studies of UGI characterization and evaluation and concluded that most approaches use methods requiring sampling and sophisticated analytical methods. The advantage of the Nat & Fun indicators and the analysis provided in this study lies in its simplicity, as it can be applied without sophisticated methods. Thus, Nat & Fun can be generalizable and help to increase the cost-effectiveness of UGI evaluations, as no expensive equipment is required and, at the same time, they provide an acceptable accuracy (the approach was able to detect meaningful groupings of UGI according to their environmental features). Previous studies used numerous ecological indicators (12 in the case of the European Environmental Agency (European Environmental Agency EEA, 2017) to assess UGI performance and focused on ES assessment (Fernández de Manuel et al., 2021), very time-consuming and expensive procedures were required to obtain the data needed to assess ES properly (Brouwer et al., 2003). The Nat & Fun indicators also satisfy the need for the unification of indicators (Tudorie et al., 2019) in order to assist cities in developing objective and adequate urban planning of UGI. Complementarily, the further assessment of ES provided by the UGIs of Zaragoza and its relationship with Nat and Fun indicators will allow a complete overview of the performance of Nat and Fun, not only as a surrogate of the UGI performance but also on the potential supply of valuable ES.

The use of complex methods is minimal in our approach but is mainly focused on an ecological perspective. Further development of this approach could also include social and economic variables and their relationship with the Nat and Fun indicators used here. Additionally, this study didn't incorporate the use of remote sensing even though remote sensing is responsible for producing a virtual explosion of growth in ecological investigations and applications (Cohen and Goward, 2004). Future research can substitute the use of Google Earth and ArcGIS (Vector) by using image classification in remote sensing (e.g. Xu et al., (2020)). Moreover, the number of variables used in this study could be considered high (15) and could have been reduced. Further investigation is needed analyzing a smaller number of variables representing other characteristics than the ones presented in our study.

5. Conclusion

The UGI of Zaragoza city was mostly characterized by sites designed

with regular shapes and a dominance of artificial components distributed throughout the densely urbanized area of the city. However, there was also a small group of sites, covering a large area, with a high cover of natural components and driven by natural processes (river meanders, floodplains, forests), mostly located in suburban zones. A similar pattern has been found in other European cities (Capotorti et al. 2017), so the framework proposed here for the assessment of the UGI network could be applicable in other cities and countries. The evaluation of Nat and Fun indicators seems an efficient tool to obtain an overview of the characteristics of the green zones of a city, the potential changes to be implemented in existing UGI sites and the design of new ones, to reach a more balanced representation of ecosystem processes, functions and services within the UGI network of a city.

A strong negative relationship was observed between the proportion of artificial area and of regular design and the Nat and Fun indicators, which suggests a high potential of these variables to act as indicators of UGI performance. Our results indicate that the improvement of naturalness and functioning of UGI sites can be achieved by minimizing regularity (regular design), hence preserving the natural topological relief and decreasing the area of soil covered by artificial components.

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CRediT authorship contribution statement

Elie Hanna: Investigation, Data curation, Visualization, Writing – original draft, editing, review. **Dani Bruno:** Writing – review & editing, Methodology. **Francisco A. Comín:** Investigation, Writing – original draft, editing, review, Supervision.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2022.127825.

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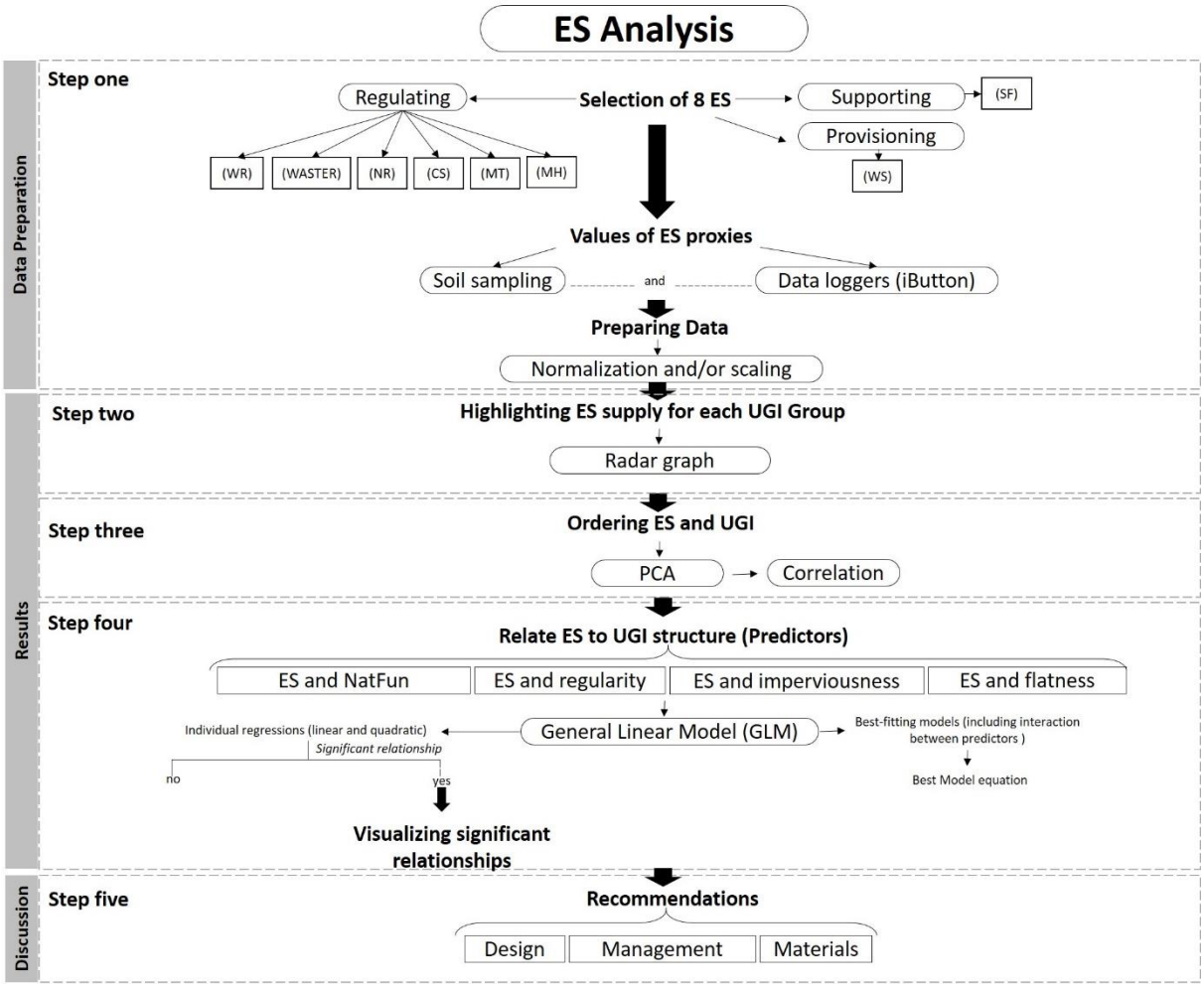

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The ecosystem services supplied by urban green infrastructure depend on their naturalness, functionality and imperviousness

Elie Hanna[1,2] · **Daniel Bruno**[3] · **Francisco A. Comín**[1]

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Abstract

Urban green infrastructure (UGI) can provide key ecosystem services (ES) for human well-being. For this purpose, it is critical to ascertain which characteristics regulate the provision of ES by UGI. In this study, eight ES (water supply, water regulation, waste regulation, nutrient regulation, soil formation, carbon sequestration, air temperature regulation and air humidity regulation) of thirty UGI sites of Zaragoza (Spain), were evaluated using proxy indicators derived from analyzed soil samples, and in-situ measured air temperature and humidity. A principal component analysis was performed to group different ES, and to study the dispersion of different types of UGI along the distinct ES. Additionally, relationships, between the evaluated ES and predictors; flatness, imperviousness, regularity, naturalness and functioning of the UGI sites were studied through linear and quadratic regressions. Large UGI sites such as riparian zones, meanders and natural forests showed relatively high values of ES in contrast with more artificial sites. Moreover, the study showed that water supply, water regulation, soil formation, carbon sequestration and air temperature regulation were significantly and positively related to ecological naturalness and functioning, while imperviousness was the main predictor explaining the reduction of five ES. Our findings provide evidence for the existence of important interactions between predictor variables and ES in UGI. It also showed that the provision of urban ES can be improved expanding the variety and type of green infrastructure sites, decreasing impervious area, and increasing the naturalness and functioning of UGI.

Keywords Ecosystem services · Urban green infrastructure · Imperviousness · Naturalness · Functioning

Introduction

There is an increasing interest on improving the green infrastructure of urban zones (UGI) because of the global urban sprawl which causes degradation and fragmentation of natural ecosystems (Mcdonald et al. 2018; Behnisch et al. 2022), and the challenge ahead for urban zones to develop an operational network of green sites supplying benefits to their inhabitants (Hogan and Ojima 2008; Kabisch et al. 2015).

UGI refers to the integration of systems with natural components into the built environment. Both terrestrial (green) and aquatic (blue) ecosystems are included here, although UGI is more generally used to simplify. The variety of UGI sites ranges from parks and green roofs to trees, wetlands and other natural systems (Goddard et al. 2009). Due to their environmental, economic and social benefits, UGI is increasingly recognized as an integral part of sustainable urban planning and development (Grimm et al. 2008), and there is growing interest in integrating green infrastructure into urban environments as they can contribute to sustainable development and human welfare (Chatzimentor et al. 2020; Hanna and Comín 2021). These benefits are called ecosystem services (ES) which are necessary for the well-being of urban citizens (Reid et al. 2005b). ES are traditionally classified into regulating services (e,g, carbon sequestration)

✉ Elie Hanna
812719@unizar.es

Daniel Bruno
dbrunocollados@um.es

Francisco A. Comín
comin@ipe.csic.es

[1] Instituto Pirenaico de Ecología, Consejo Superior de Investigaciones Científicas-CSIC, 50059 Zaragossa-Jaca, Spain

[2] Department of Agricultural and Natural Environment Sciences, Higher Polytechnic School, University of Zaragoza, 22071 Huesca, Spain

[3] Department of Applied Biology, Miguel Hernandez University, 03202 Elche, Spain

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(Lal et al. 2013), provisioning services (e,g., food production) (Holt et al. 2016), supporting services (e,g., soil formation) (Dominati et al. 2010), and cultural services (e,g., educational values) (Daniel et al. 2012). Although regulating services are more complex, recent natural disasters and the negative impacts of climate change have brought them to the public's attention (Krkoška Lorencová et al. 2016). For instance, there is a growing interest in buffering heat waves through UGIs to mitigate the urban heat island effect (Kabisch et al. 2017; Marando et al. 2018).

A growing amount of scientific literature targeting ES evaluation have been produced as a result of the increased interest in UGI (Haase et al. 2014). The methods applied to assess ES differ for each type of service. For instance, cultural services are often based on surveys and interviews (Francis and Jensen 2017). However, regulating and supporting services depend on basic data obtained through field sampling or experimentally (Prudencio and Null 2018), whereas economic valuation is frequently adopted to evaluate provisioning ES (Wiafe 2016). Additionally, different types of contrasts are frequently used to compare ES delivery between UGI types (e.g., urban park versus natural forest), or between gradients (e.g., gradient of imperviousness, gradient of naturalness) (Veerkamp et al. 2021), or between different cities (Larondelle and Haase 2013).

A case-specific combination of different types of UGIs and features of their components can buffer the local effects of climate change (Baró et al. 2014) but also mitigate global ones through the uptake of greenhouse gases (Gómez-Villarino et al. 2021; Kabisch et al. 2017). Therefore, to fight against the negative impacts of climate crisis, especially in cities, policy makers and urban planners need to focus on climate regulation by the implementation of climate-smart policies to enhance regulating ES such as carbon sequestration (Campos et al. 2022). Accordingly, it is essential to quantify ES (especially regulating ES) and to study their relationships with structural and functional characteristics of UGI elements and sites (e.g., plant cover and soil erosion). An UGI site is composed of natural and artificial components. Machado (2004) proposed a naturalness index defined by how much of the total area of a site, is occupied by natural components. Hanna et al. (2023) added functioning (Fun), defined as how much of the total area is affected by natural dynamics preserving its hydro-geomorphological aspects and ecological processes, to naturalness (Nat), hence creating the Nat&Fun index. The latter study suggested that increasing Nat&Fun might increase ES delivery hence attempting to link ES delivery to natural components and functions of the UGI site.

ES supply should be systematically incorporated into urban planning and policy, to ensure sustainable development (Rall et al. 2015). A recent survey addressed to policy makers, researchers and stakeholders from 15 European countries about the integration of the ES framework in European city planning showed the disagreement between policy makers and researchers with respect to the main obstructions to enhance or improve green urban areas design (European Commission. Joint Research Centre 2015). Researchers perceived a low public awareness and political interest, whereas policy makers and other stakeholders had a more optimistic point of view. All types of participants agree that the main obstacles to a better implementation of UGI are competing interest from the building sector and lack of financial means. This is paradigmatic since investing in UGI may often be economically advantageous (Elmqvist et al. 2015).

Then, there are many positive evidences to enhance the evaluation of ES provided by UGI as a tool for guiding urban planning in a sustainable way. In this study, we aim to: 1) quantify the contribution of different UGI types to the provision of key regulating (carbon sequestration and water, climate, waste and nutrient regulation), supporting (soil formation) and provisioning (water supply) ES; 2) identify the relationships between UGI elements and ES delivery; 3) and between each ES and gradients of structural variables (regularity, flatness, imperviousness, Nat&Fun) to test its usefulness as predictors or drivers of ES supply. We hypothesized that UGI supplies key ES in a medium-sized city, whose magnitude of delivery is positively related to a natural and functional structure and Nat&Fun index but negatively to regularity, flatness and imperviousness. Furthermore, we speculate that the UGI sites with the same characteristics (correspond to the same group) agglomerate together and could deliver the same ES and with similar magnitude. With this study we contribute to a better understanding of the influence of various structural components of UGI and their impact on the supply of multiple ES, which can help to develop more cost-effective strategies for a true integration of green infrastructures into the urban environment.

Methods

Study site

The research area corresponds to the city of Zaragoza located in the autonomous community of Aragon in NE Spain, which is a medium-size city (van den Berg et al. 2017), and has a population of 693,229 and a land area of 967 km^2 (Fig. 1).

The Zaragoza UGI is made up of natural, semi-natural, and man-made areas that include both terrestrial and aquatic ecosystems. Some of them are tiny locations in the most densely populated area of the city, but the majority of the relatively sizable green areas (river banks, forests, and meanders) are found in the peri-urban areas surrounding the city.

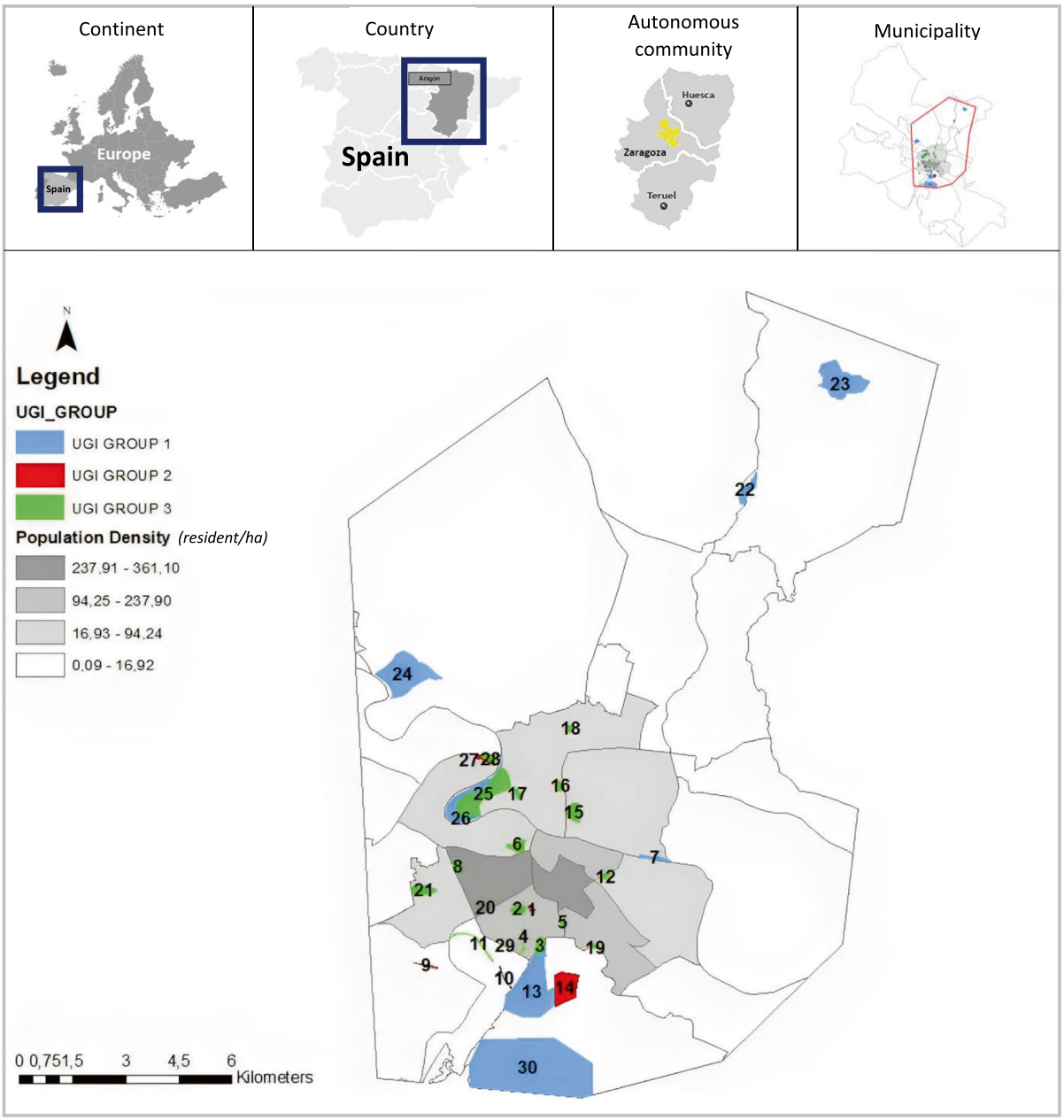

Fig. 1 Study area corresponding to the city of Zaragoza (Spain). This map shows the typology of the sampled UGI sites that we visited and sampled in relation with the population density of the city (inhabitants/km^2). (Check Table S1 for more details on the UGI sites and to which UGI group they belong)

In this study, 30 UGI sites representing the variety of UGI sites of Zaragoza were visited (Table S1) and data for the estimation of ES supply were taken (Fig. 1). These 30 sites covered proportionally a wide range of types of UGI sites (represented by the 89 sites studied in Hanna et al. 2023), and they showed a high data variability representing that range of types of sites. Thus, the number of UGI sites of each type was selected to look for a balanced proportion relative to the area occupied in Zaragoza city. Urban park was the predominant type of UGI in the city, being an important part of the complex urban ecosystem network providing significant ES, so 13 out of the 30 sampled UGI sites corresponded to the category of urban parks. The other types sampled were canal, urban forest, river (2 units each category), cemetery, community garden, agricultural land, roundabout, square, street trees, university park (1 unit each one), located in the urban zone, and steppe, forest and meander located in the peri-urban zone.

In order to attribute ES values to different types of UGI and to test our hypothesis that UGI with similar characteristics could deliver the same magnitude and range of ES, we used the data of a previous study (Hanna et al. 2023),

in which 89 sites were ordered in a multidimensional space according to their shared socio-ecological features using a Principal Component Analysis (PCA), forming 3 groups/clusters of UGI sites with similar features. From the latter research, we selected 30 UGI sites (of the 89) to be sampled, and based on the PCA figure found in Hanna et al. (2023), these 30 sites were divided into 3 groups: UGI Group 1 incorporates rivers, meanders, urban forests, forests, an urban park and steppes, with relatively large areas, spontaneous vegetation developed naturally over undisturbed soils, and a high regulation by natural hydro-geomorphological factors; UGI Group 2 included street trees, square, artificial canal, cemetery, community garden, which are UGI sites characterized by artificial components and highly managed by human actions; UGI Group 3 consisted of urban parks, agricultural land, university parks, canal, and roundabout, which represent UGI sites located in flat areas with transplanted soil and vegetation characterized by regular plantations, but still with some degree of dependence on natural hydro-climatic factors.

Data collection and analysis

The first step was the selection of 8 regulating, supporting and provisioning ES to measure based on their ecological importance (Table 1). They include ES that have a significant impact on human well-being and urban sustainability (Reid et al. 2005a), and on a capital environmental crisis as climate change (Bartesaghi-Koc et al. 2018; Demuzere et al. 2014). Due to their importance in relation with global change and its strong relationship with human welfare (Mengist et al. 2020), 6 out of 8 ES are regulating services: water regulation, waste regulation, nutrient regulation, carbon sequestration, temperature and humidity regulation. The other 2 ES corresponded to a provisioning (water supply) and a supporting (soil formation) service which are essential for human life and ecosystem functioning.

In each UGI site, 3 soil samples, separated 20-200m from each other, at a depth of 0–20 cm in the vegetated area were taken in each UGI site in order to assess water supply (WS), water regulation (WR), nutrient regulation(NR), soil formation (SF), carbon sequestration (CS) and waste regulation (WASTER) using proxy indicators based on Dominati et al. (2010, 2014) and Schaber et al. (2019). Assessing temperature regulation (MT) and humidity (MH) regulation was performed using data recorders (iButton®) that took hourly measurements during 1 month in the warmer period of the year (July–August 2022) to estimate daily air temperature and humidity oscillation. Thus, 6 data loggers covered with a double plastic cap (the lowest one leaky to let the air flow) were placed in each UGI site at 1.5–2.5 m height (3 data loggers were placed under the shade of trees, 3 exposed to the sun hanging from walls or statues but not over cemented areas), in locations not obstructed by objects, buildings or other structure that can distort the readings. MT and MH data were then upscaled to the whole UGI site according to the area (square-meters) occupied by vegetation in relation to the total area of the UGI site, to quantify the relative contribution of ES supply (ES/m^2). Finally, these data were normalized for subsequent statistical analysis.

The second stage consisted of estimating the relative value of ES for each UGI group. For this, a radar chart was performed to identify the ES supply range and magnitude for each UGI Group. Thirdly, in order to test our hypothesis that UGI sites with the similar characteristics provide equivalent ES, a principal component analysis (PCA) was performed with the data of the 8 ES evaluated (Table S2). Therefore, PCA enabled to order the 30 UGI sites individually, and in

Table 1 Selected ecosystem services, abbreviations used in subsequent tables and figures, indicators used for their evaluation, units in which they were measured, and data source

ES Group	Ecosystem Service	ES abbrev	Indicator	Unit	Data source
Provisioning	Water Supply	WS	Soil water content	%	Soil analysis
Regulating	Water Regulation	WR	Inverse of soil bulk density	$1:(g/cm^3)$	Soil analysis
Regulating	Waste Regulation	WASTER	Conductivity	µS/cm	Soil analysis
Regulating	Nutrient Regulation	NR	Reactive phosphorus available to plants	mg/kg	Soil analysis
Supporting	Soil Formation	SF	Organic matter content	%	Soil analysis
Regulating	Carbon Sequestration	CS	Soil content of total organic carbon (TOC)	% of organic C per 100 g of soil	Soil analysis
Regulating	Meteorological Temperature Regulation	MT	Average daily difference of temperature range between data from data loggers in the sun and those in the shade	°C	i-Button recording
Regulating	Meteorological Humidity Regulation	MH	Average daily difference of humidity range between data from data loggers in the sun and those in the shade	% Relative humidity	i-Button recording

UGI groups, in a multidimensional space according to the type of ecosystem services they supply. Also, to fully comprehend the significance of these principal components and understand the underlying dynamics, it is crucial to investigate their correlations. Thus, we performed a correlation analysis on the resulting PCA components. The correlation value of these ES was calculated using the Spearman Method (Table 2).

Fourthly, we assessed ES delivery (Veerkamp et al. 2021), through studying their relationships with 4 characteristic features of UGI sites that are heavily involved in the design process and planning of UGI sites (Check Table S3 for details). Thus we compared ES supply along gradients of 1) naturalness and functioning (NatFun), calculated as the average value of the sum of the individual values of naturalness and functioning of each UGI site (Larondelle and Haase 2013, 2) green versus grey coverage (Imperviousness) estimated as the percentage of impervious surfaces relative to the total area of the UGI; 3) regularity, calculated as the percentage of the area occupied by regular and artificial forms relative to the total area of the UGI site. 4) flatness; leveling of the surface, estimated as the percentage of flat area relative to the total area of the UGI site. All these variables were used as predictor variables to provide information about the possible causes or factors that influence ES supply by UGI sites.

For this, individual regressions were performed to detect which variables were related to the supply of ES (Fig. 2). We tested the significance of simple and quadratic terms for each z-standardized (mean = 0, SD = 1) variable as well as the pairwise interaction terms to look for potential combined effects. Finally, we used the R package *glmulti* to automate model selection and identify the best-fitting model, based on the Akaike Information Criterion (AIC) and considering two-way interactions between all predictors (Calcagno and de Mazancourt 2010). Prior to this analysis, NatFun predictor was logarithmically transformed to reduce skewness, and all predictors were standardized to improve linearity against response variables and ensure normal error distributions and homogenous variance. We also used the percentage of explained deviance to evaluate model performance. We visually checked homoscedasticity and normality of residuals.

Finally, based on the information we got from the data analysis, recommendation for the design, planning and management of the UGI site were given to face the challenges of climate change (Fig. 2).

Results

Highlighting ES supply for each UGI group

The distribution of ES values in the radar chart (Fig. 3) showed that the average (after standardization × 100) relative values of ES obtained for each UGI group pointed to a low general provision of ES; i.e. all ES values were < 50 in the three groups (Fig. 3), which were particularly reduced for SF and WR. UGI Groups 1 and 2, which may have areas with dense and tall vegetation showed relatively high values of MT.

UGI Group 1 (river, meanders, urban forest, steppe, natural forest and an urban park) showed relatively high values of MT (48.53) and WS (34.9), followed by MH (31.7) and CS (18.46), but very low values of WASTER (9.73), NR (11.59), WR (5.84), and especially for SF (0.14). The highest values of UGI Group 2 (street trees, square, canal, cemetery, community garden) were found for MT (32.4), MH (22.12), followed by NR (18.23) and WS (14.36), whereas CS (9.37), WASTER (4.96), WR (1.75), and SF (0.08) displayed reduced or very reduced values in the case of the latter ES. UGI Group 3 (urban and university parks, roundabout, canal, agricultural land) showed relatively high values of MH (42.62), WS (28.2), NR (24.1), MT (21.37), CS (17.4) and WASTER (13.3), but very reduced values of WR (3.2) and SF (0.15).

Table 2 Correlation coefficients (* indicates significant correlations at $p < 0.05$) between 8 ES: Water Supply (WS). Water Regulation (WR), Waste Regulation (WASTER), Nutrient Regulation (NR), Carbon sequestration (CS), Soil Formation (SF), Temperature (MT) and Humidity Regulation (MH). Check the correlation matrix Fig. S2 in Supplementary materials

ES	*WR*	*WASTER*	*NR*	*SF*	*CS*	*MT*	*MH*
WS	0.6 *	0.28	0.17	0.4 *	0.47 *	0.21	0.24
WR		0.46 *	0.34	0.55 *	0.43 *	0.41 *	0.24
WASTER			0.24	0.43 *	0.45 *	0.09	0.32
NR				0.15	0.33	0.03	0.51 *
SF					0.81 *	0.26	0.13
CS						–0.03	0.3
MT							–0.07

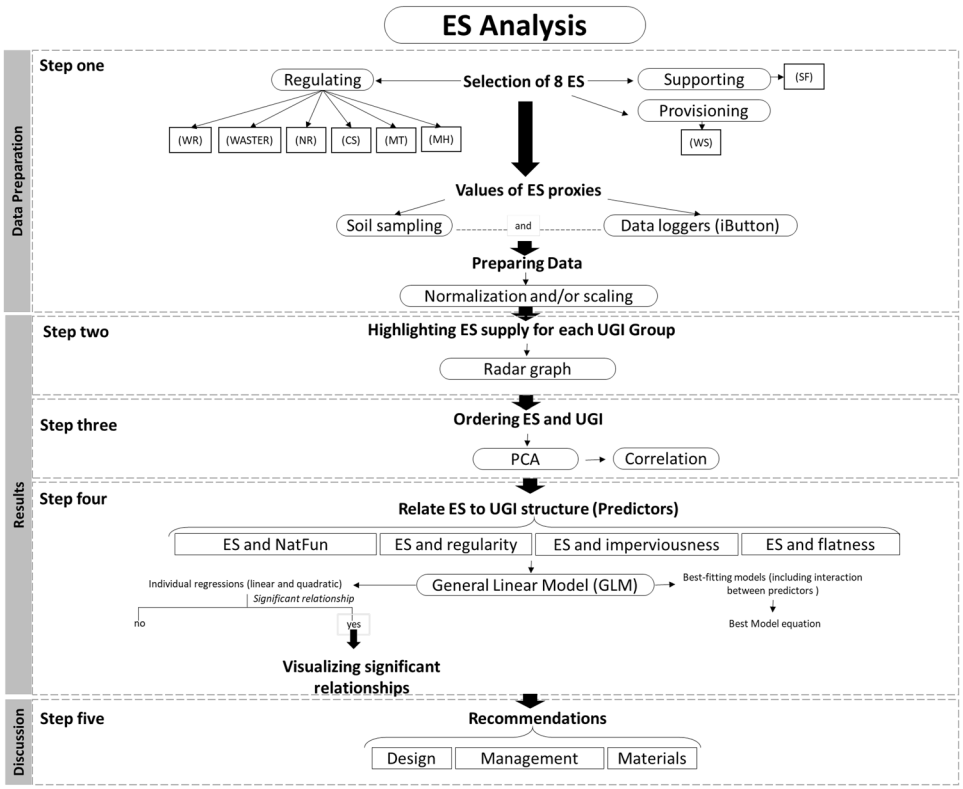

Fig. 2 Methodology used for the assessment of ecosystem services (ES) and data analysis. Water Supply (WS), Water Regulation (WR), Waste Regulation (WASTER), Soil Formation (SF), Nutrient Regulation (NR), Carbon sequestration (CS), Temperature (MT) and Humidity Regulation (MH)

Ordering ES and UGI

The results of the PCA that were used to test our hypothesis that UGI sites with the same characteristics provide the same ES showed that the two first axes of the PCA analysis accumulated 51.3% of variation among UGI sites in relation to their supply of ES (PC1 = 29.9%; PC2 = 21.4%). PC3 represented a smaller data variability (18.27%) and the ordination of variables was very similar to that of PC2. The rest of PCs represented a low data variability, less than 12% each one (Table S4). Accordingly, we retained the two principal axes since they represent most environmental variability and the main gradients in the sampled sites.

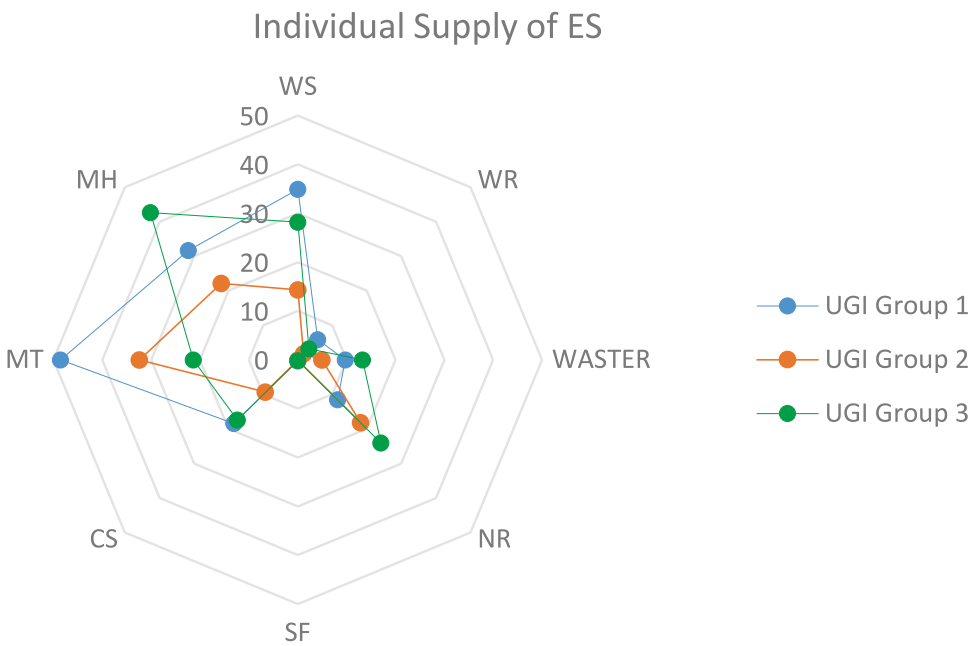

Fig. 3 Radar chart (spider net) graph of ES individual supply for each group of UGI elements. WR = Water Regulation, WS = Water Supply, WASTER = Waste Regulation, NR = Nutrient Regulation, CS = Carbon sequestration, MT = Temperature Regulation, MH = Humidity Regulation, SF = Soil Formation

PC1 represents the relative ES supply of UGI. PC1 was negatively correlated with all the ES assessed and represented a gradient from sites with a reduced ES supply on the right to sites with a greater magnitude of ES supply on the left (Fig. 4). For example, the point on the far right of axis 1 corresponded to the UGI site steppe, which displayed very low relative values of ES (No. 30 in Table S1). It represents a typical semiarid steppe: poor in nutrients and with a predominance of gypsum soils in the peri-urban zone of Zaragoza city (Fig. S1). The differences with other types of UGI sites in terms of landscape, soil features and fauna and flora, translated into a reduced and different ES supply. On the far left of axis 1, two meanders with relatively high ES values are represented (No.22, No.24 in the peri-urban zone of Zaragoza), which are large natural areas that still maintain their hydro-geomorphological aspects.

PC2 correlated positively with 5 ES (NR, MH, MT, WS, WR) but negatively with 3 ES (WASTER, SF, CS). This contrasting pattern points to a trade-off between the ES more related with functional characteristics (NR, WR, WS, MH, MT) that support key ecological processes (soil nutrient removal, soil infiltration capacity, soil retention capacity, and buffering effects of the vegetation on humidity and temperature daily changes), and structural characteristics of the

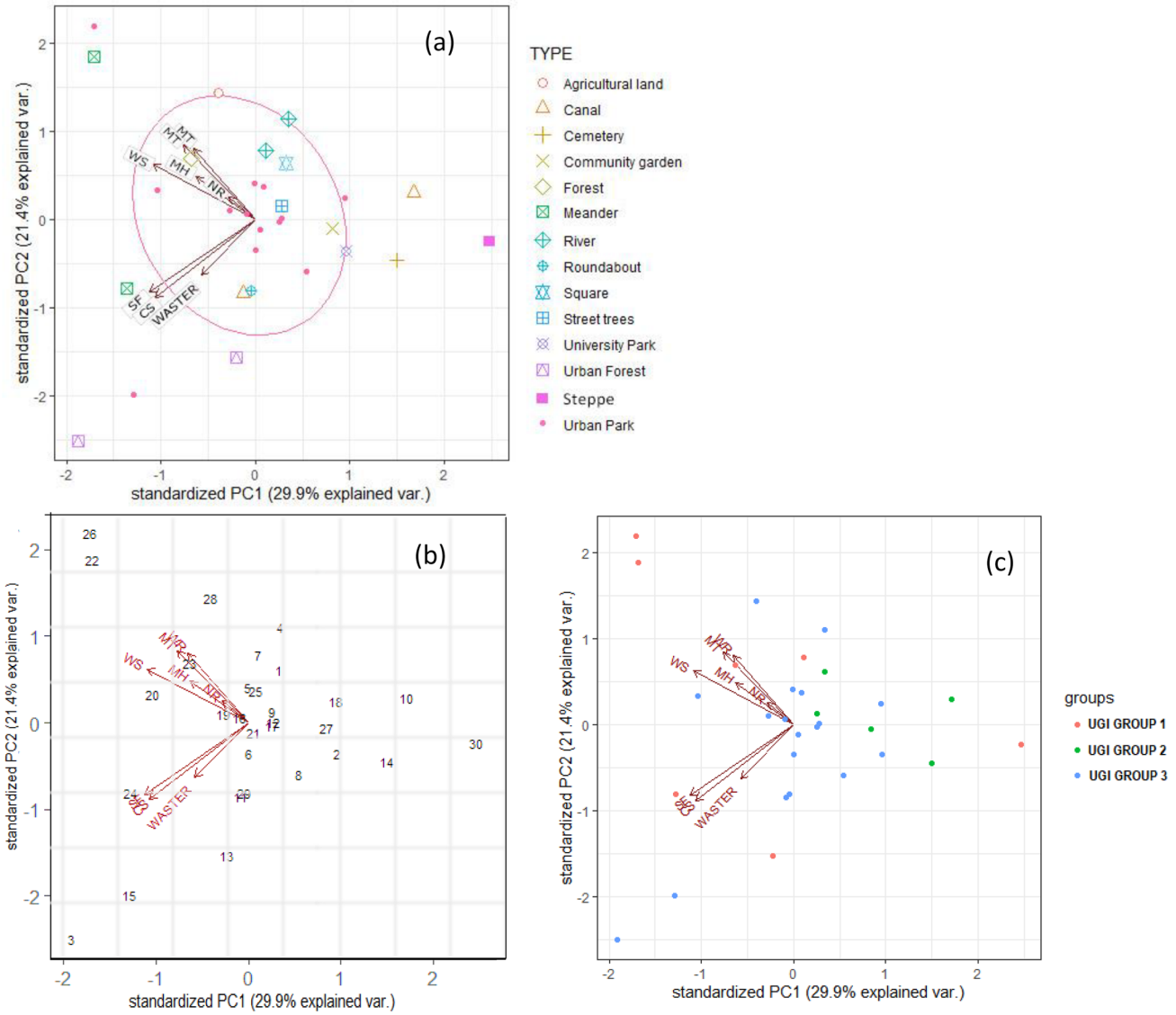

Fig. 4 **a** PCA ordination (using first two axes) of UGI sites according to their supply of ES: **b** each number represented a UGI site found in Table S1; **c** showed the distribution of different UGI sites corresponding to each UGI Group. Water Supply (WS). Water Regulation (WR), Waste Regulation (WASTER), Nutrient Regulation (NR), Carbon sequestration (CS), Soil Formation (SF), Temperature (MT) and Humidity Regulation (MH)

soil which are mainly related to the supply of SF, CS and WASTER. Accordingly, the most natural UGI sites (Nos. 26 and 22, two river meanders) characterized by a good conservation of their natural processes and dynamics were in the top end, while large UGI sites (Nos. 15 and 3, two large urban parks) which are managed artificially were in the most negative side of the PC2. These two UGIs (Nos. 26 and 22) were characterized by a combination of natural vegetated zones with long-time planted gardens, which could have impaired UGI functionality and its associated supply of key regulating ES as NR, WR, MH and MT. In summary, this distribution could indicate that the nature of the UGI sites (artificial or natural) was related with the supply of different types and magnitude of ES.

A mixture of different types of UGI sites is observed in the space defined by the two major principal components (Fig. 4a) which could reflect the variety of UGI sites and the variety of management and ecological conditions for similar UGI sites. The results also showed that sites belonging to UGI Group 3 were located in the center forming a cluster (Fig. 4a, c) with some exceptions (Parque Grande-Natural Zone No.3, and Parque Tio Jorge No. 15). Sites belonging to UGI Group 2 are located on the positive part of the PC1, which is the area representing reduced supply of ES, and some elements are in the cluster formed in majority by UGI Group 3 (Plaza San Francisco No.1, and sreet trees No.9). On the other hand, we observed a notable dispersion of the elements of sites belonging to UGI Group 1, which is composed of very different ecosystem types, inside the PCA graph.

Building upon the PCA results, the correlation analysis delved deeper into the interconnections between ES. Our results indicated that WS was significantly correlated with 3 ES; WR (correlation coefficient $r=0.6$), SF ($r=0.4$) and CS ($r=0.47$). In addition, we found that 4 other ES are significantly correlated with WR; WASTER ($r=0.46$), SF ($r=0.55$), CS ($r=0.43$) and MT ($r=0.41$). Furthermore, WASTER is also significantly correlated with two other ecosystem services: SF ($r=0.43$) and CS ($r=0.45$). NR is significantly correlated with one ecosystem service, MH ($r=0.51$). Finally, we observed a significant correlation between SF and CS ($r=0.81$), in addition to the correlations mentioned previously (Table 2).

Relate ES to UGI structure (predictors)

Individual regressions showed that WS, WR, SF, CS and MT were significantly and positively related to LogNatFun ($p<0.05$ in all cases; Fig. 5; Table 3). However, they differed in the amount of explained variance (goodness of fit, R^2). LogNatFun was positively related to MT ($R^2=0.298$; quadratic relationship), followed by WS ($R^2=0.209$; quadratic relationship), WR ($R^2=0.173$), and finally to SF and CS ($R^2=0.1$). Regarding significant quadratic relationships, convex and concave relationships were found between LogNatFun and MT and WS, respectively.

Imperviousness was the main predictor explaining reduced WR, WS, CS and SF ($p<0.04$ in all cases). They also differed in the amount of explained variance. Imperviousness was strongly negatively related to WR ($R^2=0.27$), followed by WS ($R^2=0.243$), then SF ($R^2=0.143$), and finally CS ($R^2=0.123$). Therefore, compared to LogNatFun, Imperviousness showed a stronger relationship with all ES (except MT), especially with WR. We also detected a quadratic concave relationship between Regularity and MT, where Regularity was negatively related to MT ($p=0.016$, $R^2=0.2$). Finally, Flatness was negatively related to WS ($p=0.04$, $R^2=0.11$). Both have a minor individual influence on ES supply in comparison with Imperviousness and LogNatFun.

There was a negative interaction between LogNatFun and Imperviousness on WS (Fig. 6a). It seems that the negative effect of imperviousness was particularly acute when LogNatFun was reduced (Fig. 6a). Additionally, there was a negative interaction between LogNatFun and Imperviousness on WR. It seems that the negative effects of imperviousness on WR were more intense when occurring in relatively natural and functional UGIs (high LogNatFun value; Fig. 6b). The service MT was also modulated by several predictors' interactions. Thus, LogNatFun was positively associated to MT but only when imperviousness (Fig. 6c) or regularity (Fig. 6d) of the UGI site was low. Finally, imperviousness and regularity displayed a significant antagonistic interaction, i.e., although they had negative effects when acting in isolation, these impacts seem to be buffered when both predictors were high (Fig. 6e).

Discussion

In this paper we advance in the assessment of how different features and types of UGIs supply a different combination and magnitude of provisioning, supporting and, regulating ES, as well as the potential trade-offs and synergies between them(Dade et al. 2018). This study responded to the need for such comparison between different types of UGI sites (De Valck et al. 2019). In fact, to the best of our knowledge a comparative study assessing the same type of ES was lacking. In order to make informed decisions on the design and management of these ecosystems, it is essential to comprehend the relative advantages and disadvantages of

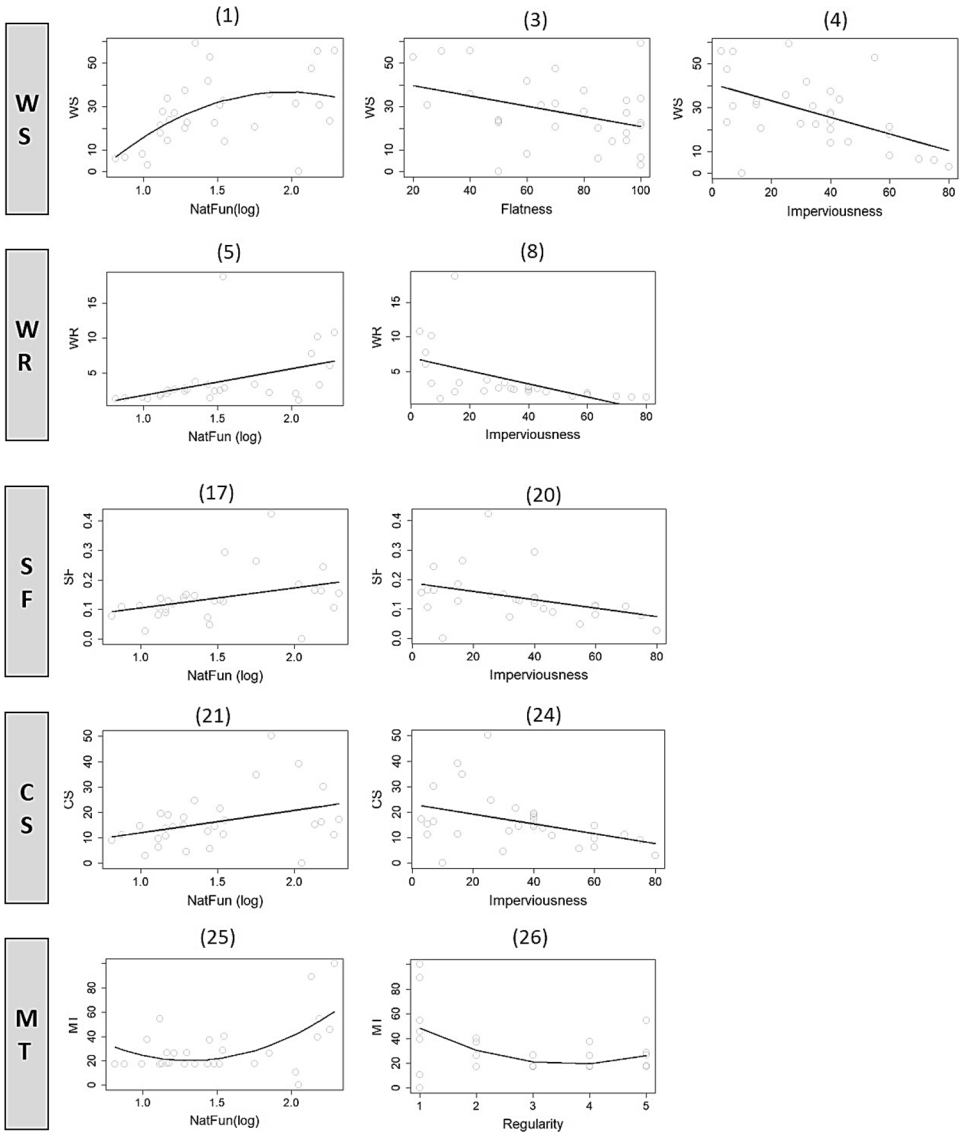

Fig. 5 Linear and quadratic regression plots showing significant (p-value < 0.05) relationships between predictors and WS (Water Supply), WR (Water Regulation), SF (Soil formation), CS (Carbon Sequestration) and MT (Temperature regulation)

the structural and functional features of UGI in providing multiple ES (Van Oijstaeijen et al. 2020), their drivers of change and the underlying mechanisms linking these drivers to ecosystem service outcome (Dade et al. 2018).

Assessing potential differences of ES provision between various types of UGI is crucial to effectively guide appropriate green infrastructure design and integrate green infrastructure into urban development strategies (Kain et al. 2016). Among the different ES evaluated, temperature regulation was the one which was supplied with greater magnitude by UGI Group 1 (river, meanders, urban forest, steppe, natural forest) and UGI Group 2 (street trees, square, canal, cemetery, community garden), whereas its supply in UGI Group 3 is much lower (Fig. 3). Cities act as heat islands due to the dominance of impervious surfaces, and lack of large natural green spaces (Abdulateef and Al-Alwan 2022). There is a high social demand for temperature regulation through the investment in functional UGI (Akbari et al. 2016). The temperature regulation capacity of UGI has been studied extensively, and our results support the notion that UGI can significantly contribute to regulate temperature and mitigate urban heat island (Shao and Kim 2022). Hence, our study supports the significance of UGI in climate change mitigation and adaptation. According to our outcomes, the maintenance and construction of large functional UGIs dominated by natural processes, dynamics and structures, that display irregular shapes, permeable surfaces and undisturbed hydromorphology can counteract the expected increase in urban temperature that can threaten the livability of urban areas in the short term as consequence of global warming (Ramyar

Table 3 Linear and quadratic regression summary of the 8 ES with 4 predictors. *P*-values (significant coefficients in bold type)

Indicator	*Model*	*Variables*	*Std Error of the Estimate*	*Adjusted R Square*	*p-value*	*Equation of the model*
WS	(1)	Log(NatFun)	50.59	0.209	**0.0158**	-22.68Log(NatFun)^2 + 88.99 Log(NatFun) - 50.47
		Log(NatFun)^2	15.72			
	(2)	Regularity	1.900	0.046	0.132	-2.948Regularity + 36.71
	(3)	Flatness	0.1105	0.110	**0.040**	-0.236Flatness + 4.448
	(4)	Imperviousness	0.1182	0.243	**0.003**	-0.379Imperviousness + 40.827
WR	(5)	Log(NatFun)	1.435	0.1735	**0.012**	3.821Log(NatFun) -2.054
	(6)	Regularity	0.460	-0.0152	0.4582	-0.34Regularity + 4.7
	(7)	Flatness	0.0278	-0.025	0.594	-0.014Flatness + 4.7
	(8)	Imperviousness	0.027	0.2789	**0.001**	-0.094Imperviousness + 6.96
WASTER	(9)	Log(NatFun)	5.121	-0.025	0.595	2.752Log(NatFun) + 7.028
	(10)	Regularity	1.474	-0.015	0.465	1.090Regularity + 7.71
	(11)	Flatness	0.087	0.015	0.238	-0.105Flatness + 18.665
	(12)	Imperviousness	0.1006	0.030	0.177	-0.139Imperviousness + 16.015
NR	(13)	Log(NatFun)	8.038	-0.002	0.347	-7.682Log(NatFun) + 31.679
	(14)	Regularity	2.317	0.003	0.305	2.417Regularity + 12.667
	(15)	Flatness	0.1396	0.002	0.311	0.143Flatness + 9.927
	(16)	Imperviousness	0.164938	-0.035	0.992	0.001Imperviousness + 20.182
SF	(17)	Log(NatFun)	0.03259	0.103	**0.045**	0.068Log(NatFun) + 0.037
	(18)	Regularity	0.009658	0.058	0.104	-0.0162Regularity + 0.189
	(19)	Flatness	0.0006028	-0.011	0.422	-0.0004Flatness + 0.173
	(20)	Imperviousness	0.009658	0.143	**0.039**	-0.001Imperviousness + 0.188
CS	(21)	Log(NatFun)	4.292	0.1	**0.048**	8.847Log(NatFun) + 3.177
	(22)	Regularity	1.265	0.066	0.091	-2.212Regularity + 23.279
	(23)	Flatness	0.07888	-0.002	0.343	-0.075Flatness + 21.791
	(24)	Imperviousness	0.08557	0.123	**0.032**	-0.192Imperviousness + 23.126
MT	(25)	Log(NatFun)	64.88	0.298	**0.003**	42.72Log(NatFun)^2 -112.42Log(NatFun) + 94.21
		Log(NatFun)^2	20.16			
	(26)	Regularity	12.934	0.206	**0.016**	4.019Regularity^2 -29.616Regularity + 73.845
		Regularity^2	2.146			
	(27)	Flatness	0.1595	-0.001	0.335	-0.156Flatness + 40.755
	(28)	Imperviousness	0.1770	0.083	0.066	-0.338Imperviousness + 41.434
MH	(29)	Log(NatFun)	8.762	-0.032	0.771	-2.57Log(NatFun) + 40.491
	(30)	Regularity	2.520	-0.021	0.534	1.586Regularity + 31.695
	(31)	Flatness	0.15265	-0.034	0.839	0.031Flatness + 34.423
	(32)	Imperviousness	0.17647	-0.027	0.633	-0.085Imperviousness + 39.655

and Zarghami 2017). However, other ES, such as waste regulation, carbon sequestration, soil formation, and water regulation, exhibited relatively low values across most UGI types. These results are in line with previous studies, which had also highlighted the big challenges in achieving optimal performance for ES in urban environments (Elmqvist et al. 2015; Sirakaya et al. 2018). For example, our investigation on the carbon sequestration ES aligns with the outcomes of previous studies focused solely on this ES that point to a small carbon sequestration efficiency of UGIs (Chen 2015; Kavehei et al. 2018). Although the positive impact of UGI on water regulation has been consistently observed in previous research exploring the effects of UGI on water management (Dai et al. 2021), our relative low values could be due to urban parks within the city were the most studied type of UGI. Thus, this general low supply of ES could be caused by spatial restrictions within urban areas, leading to the establishment of smaller and fragmented green spaces, which can impact the overall capacity of UGI to provide essential ES, especially those that heavily depend on larger and interconnected natural sites, such as carbon sequestration and soil formation. Additionally, urban environments are prone to experience elevated pollution levels and intense human activities, affecting the ecosystem

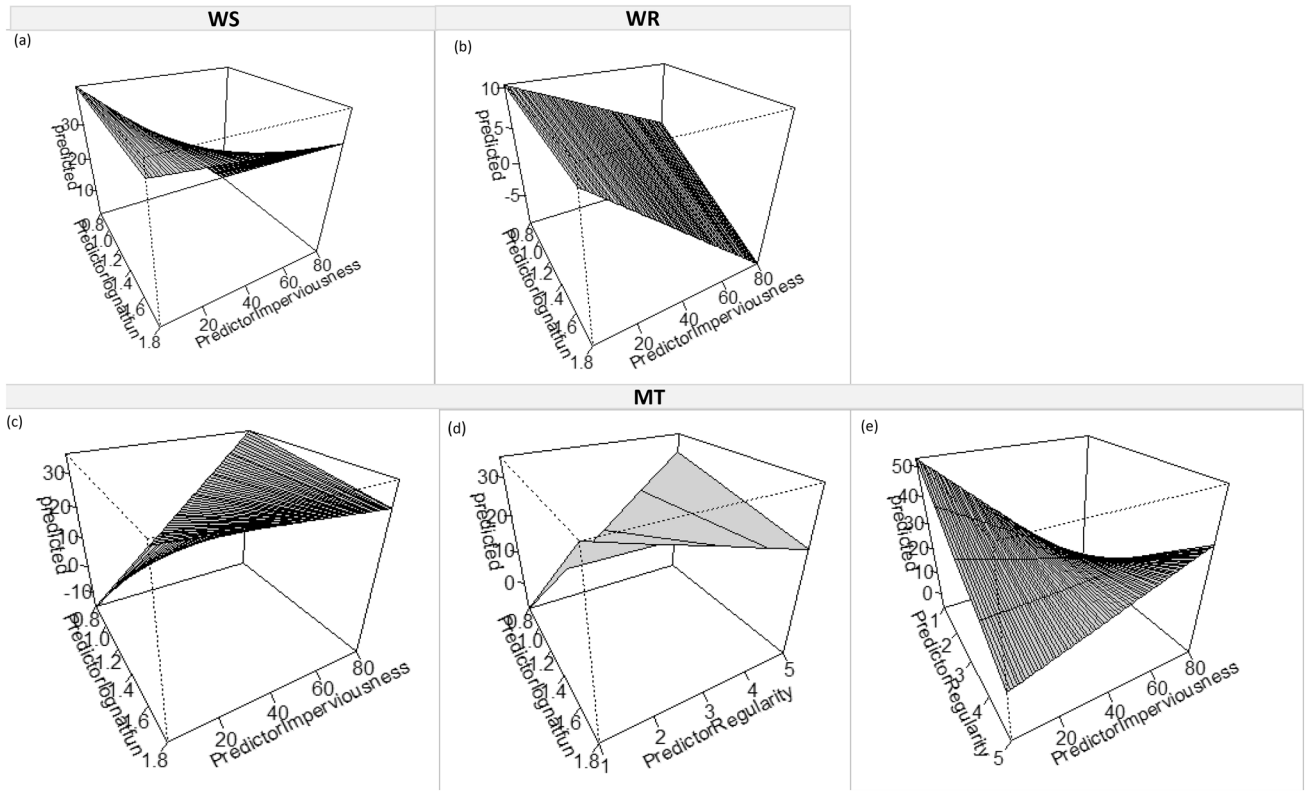

Fig. 6 **a**, **b**, **c**, **d** and **e** represent only the significant interaction ($p < 0.05$) perspective plots between dependent variables and predictors. The predicted variable represent the model equation of the interaction $Z = a*X + b*Y + c*X*Y$ (a,b and c are coefficients). WS = Water Supply, WR = Water Regulation, MT = Temperature Regulation

processes responsible for waste regulation and water regulation (McDonnell et al. 1997). A potential solution could be to improve the 3D ecological connection among the UGIs of the city. Given the lack of availability of suitable spaces, green roofs and walls could contribute to provide this benefit (Mayrand and Clergeau 2018). Furthermore, urban planners must take in consideration the creation and design of rain gardens and bioswales that can improve water regulation in the city. These sites can be designed in small places and can be a smart tool for water and waste regulation (pollutant removal), and climate city adaptation (Kasprzyk et al. 2022).

This comes in agreement with our results, that suggested that the UGI of Zaragoza could increase the supply of ecosystem services through increasing the variety of types of UGI sites, through designing new UGI sites with higher naturalness and functioning characteristics and restoring existing sites as those found in UGI Group 1 (river, meanders, urban forest, steppe, natural forest), in order to buffer the negative undesired effects of global change. Sites that belongs to UGI Group 1 delivered the greatest range and magnitude of ES supply. Similarly, Mexia et al. (2018) evaluated multiple ecosystems inside a large park (44 ha) in Portugal. This study found that a forest inside the big park scored the highest on ES delivery due to its complex natural vegetation. However, sites that belong to UGI Group 1 are large areas, and large free areas available to build UGI sites are scarce in cities, especially in the center and most populated areas. Hence the need to complement large natural and functional UGIs with smaller sites, that belong to UGI Group 2 (square, street trees, canal, community garden) and UGI Group 3(urban parks, roundabouts, agricultural land, university parks).This should be done through increasing the Nat and Fun characteristics of small and artificial UGI sites inside the city, by expanding the vegetated area of UGI sites, also reducing imperviousness; and preserving or restoring their natural hydro-geomorphological features.

It could be also argued that there is a great dispersion and diversity of UGI types within the different UGI groups. This is true, because Zaragoza's UGI encompasses a diverse array of natural, semi-natural, and artificially constructed sites, spanning both terrestrial and aquatic ecosystems. It must be noted that the UGI typology used in this study, was developed by the European Commission, https://biodiversity.europa.eu based on (Cvejić et al. 2015). Given this high variability, we needed to categorize the UGI types into three UGI groups composed of UGI elements sharing similar structural characteristics, and to study and compare their ES provision. Thus, the principal components analysis

(PCA) (Fig. 3), revealed that UGI elements that belong to the same group (share similar characteristics) did agglomerate together, especially for UGI Group 2, and UGI Group 3. Their UGI sites share similar properties because the soil is mostly artificial so soil properties can be modified systematically (Valle et al. 2022). However, in the case of UGI Group 1, we found a notable data dispersion, which could be caused by the diverse nature of UGI sites (e.g.: No. 30 is a steppe and No. 24 is a meander), which greatly condition their soil properties.

NatFun and Imperviousness were the main predictors explaining higher and reduced ES delivery, respectively. For the composite index NatFun, which considers naturalness and functioning (Hanna et al. 2023), our results suggest that more natural and functional UGIs produced a greater range and magnitude of ES delivery, especially for water supply, water regulation, soil formation, carbon sequestration and temperature regulation (Fig. 5; Table 3). Accordingly, planners and landscape designers need to 1) increase the vegetated area of UGI sites, thus increasing naturalness, 2) also to preserve valuable natural remnants of biodiversity which are still driven by ecological processes (Van Oijstaeijen et al. 2020), and 3) finally to regard the newly constructed UGI as a potential useful tool for restoring urban degraded areas and recover (at least partially) the natural dynamics associated with hydro-geomorphological processes (Klaus and Kiehl 2021), hence increasing the functionality of the UGI elements and thus its ES delivery. This is in good agreement with the hypothesis stated in the end of a previous study (Hanna et al. 2023): NatFun affects the performance on UGI elements, through their impact on the potential supply of valuable ES. Regarding the significant negative relationship between Imperviousness and ES delivery imperviousness was the main predictor explaining reduced water regulation, water supply, carbon sequestration and soil formation. This finding agrees with previous studies about the effect of imperviousness on climate change, a key factor affecting water regulation (Salerno et al. 2018) and water supply (Caldwell et al. 2012) Also this study is in alignment with a previous study that stated that pervious vegetated area enhances carbon sequestration (Velasco et al. 2016). Furthermore, as expected, the present investigation showed that imperviousness decreased soil formation. Natural soil-forming processes are frequently interrupted as urbanization and land development increase impermeable surfaces such as roads, pavements, and buildings, resulting in negative consequences on soil quality and ecosystem health (Sauerwein 2011). Although in this study the relation between temperature regulation and imperviousness was not found significant, as it was in other studies (Morabito et al. 2021; Rajasekar and Hu 2011; Yuan and Bauer 2007), the results were very close to the significance value (p-value = 0.066). This could be due to the relatively reduced number of sampled sites (30), but also that the mentioned studies used remote sensing and satellite imagery to study the relationship between urban heat island and imperviousness, whereas we used in-situ data collection through data loggers. Further research is needed, with more sample units and comparing the data of data loggers with those obtained by remote sensing. From a management perspective, restoration actions aiming to reduce impervious surfaces and the % of artificial soil in UGI element, would potentially enhance the supply of ES. However, if an artificial area (e.g., recreational area) is needed to provide cultural ES (Paracchini et al. 2014), then it would be advisable to design sustainable permeable pavement for the artificial areas interspersed with natural vegetated areas (Liu et al. 2018).

Finally, we found strong interrelationships between ES in the UGI. The study showed that water supply, soil formation, carbon sequestration, and temperature regulation are all significantly and positively correlated with water regulation. This suggests that water regulation is a key ES that can act as surrogate of several other ES. Similarly, waste regulation was found to be significantly correlated with soil formation and carbon sequestration (Table 2). These findings may provide insights into the underlying mechanisms that govern the supply of ES in UGI, as well as the ways in which they are interrelated to develop more effective strategies for conserving and restoring ES. However, our investigation could have benefited of an inclusion of a more holistic approach that also include the supply of cultural ES across UGIs (Amorim et al. 2021).

Beyond the individual effects of the predictor variables on the ES supply, we also provide evidence for interactive effects between predictors on ES. Water supply decreased as imperviousness increased, especially in UGI sites with low naturalness and functioning, as shown by individual regression coefficients and the significant interactions among predictors. Additionally, we found that the negative effects of imperviousness on water regulation were more pronounced in UGI sites with high NatFun values. These outcomes highlight the importance of designing UGI sites that are not only natural and functional but also consider the percentage of impervious surface to maximize water regulation. A recent flood event originated after heavy rains over a paved ravine and ring road of Zaragoza corroborates this issue (https://hoyaragon.es/noticias-aragon/zaragoza/barranco-muerte-rambla-riada-zaragoza). Furthermore, the positive relationship between NatFun and temperature regulation and the significant interactions found, suggest that natural and functional UGI may play an important role in regulating urban temperatures, particularly in sites with low imperviousness and regularity.

Only 4 UGI sites (13.3%) evaluated were located in the peri-urban areas, and we believe that by including more peri-urban green infrastructure sites, the study could have

provided even more valuable insights, especially if these sites are transitional zones between urban and rural areas, and can significantly help in climate change mitigation (Gómez-Villarino et al. 2021). Furthermore, we understand that the uneven sampling between urban and peri-urban areas may have resulted in the exclusion of key provisioning ecosystem services (Food production, raw materials production, energy production) as there are large areas surrounding Zaragoza city which could provide these services. In contrast, most UGI elements in densely populated neighborhoods are mostly designed and constructed with artificial components for recreational purposes. This arise the tradeoffs among ES supply, as artificial components are usually associated with impervious areas, reduced naturalness and dysfunctional UGI, and, consequently, with a diminished supply of ES.

Our work has showed that enhancing the naturalness and functionality of UGI is critical for providing a minimum range and magnitude of ES supply, confirming our hypothesis. In this way, we can ensure that urban green spaces continue to provide essential services that can mitigate the negative effects of climate change (Mathey et al. 2011), support human well-being (Lee et al. 2015), and contribute to a more sustainable and resilient urban environment (Marinelli et al. 2022). Also, the evidence from this study suggests that minimizing impervious surfaces can increase the UGI supply of ES. It could be argued that most UGI sites studied here corresponded to urban parks, at the expense of other UGI types. However, urban parks are the predominant type of UGI in a medium-city like Zaragoza (Hanna et al. 2023), because it is a source of rest, comfort and community fun in a stressful environment (Dunnett et al. 2002). Further research is needed that can englobe more UGI sites and types, especially private ones such as private allotments, backyards, and green roofs, often excluded from this kind of studies. Additional investigation can also encompass more provisioning (e.g., food production) and supporting ES (e.g., pollination), and introduce cultural ones (e.g., recreational and educational benefits), which should be addressed in relation to their drivers, as NatFun, Imperviousness, Flatness, Regularity and other potential predictors. Therefore, further analysis can include other predictors that are also involved in the design process and planning of UGI sites such as the number of plant strata, water availability and area (important for water management especially in urban areas), as well as biodiversity and connectivity between UGI elements. The challenge ahead is designing and implementing a mosaic of connected UGI sites and types combining the provision of all supporting, provisioning, regulating and cultural ES, which help to create a healthy urban environment while minimizing negative tradeoffs among ES.

Conclusion

In general, the UGI sites of a medium size city like Zaragoza provided low ES because of the lack of naturally vegetated zones (naturalness) maintained with hydro-geomorphological processes (functioning) in contrast with the dominance of impervious surfaces and artificial elements in most UGI sites. Beyond this general low provision, natural UGI elements such as river, meanders, urban forest, steppe, natural forest provided the highest temperature regulation, water supply, carbon sequestration, and water regulation. On the other hand, UGI sites such as urban and university parks, roundabout, canal, agricultural land provided the highest value of humidity regulation, nutrient regulation while waste regulation and soil formation were the lowest ES delivery across all UGI sites.

NatFun was significantly and positively associated with the delivery of 5 ES, but the percentage of impervious area was the main predictor explaining the decrease in 3 ES. Flatness and Regularity had minor but also significant negative effects on ES supply. Additionally, we found evidence for several synergistic and antagonistic interactions between predictor variables and ES in UGI.

In order to improve the delivery of ES, we propose to increase the variety of UGI sites and types, reducing the area of imperviousness and increasing (at least partially) their naturalness as well as their hydro-geomorphological processes and natural dynamics.

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Author contribution E.H and F.C conceptualization; E.H, D.B and F.C methodology; E.H and F.C formal analysis; E.H, D.B and F.C investigation; F.C resources; E.H data curation; E.H and F.C writing—original draft preparation; E.H, D.B and F.C writing—review and editing; E.H visualization; F.C supervision.

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Availability of data and material All data available upon request.

Declarations

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Research involving humans and/or animals Not applicable.

Consent for publication All authors confirm submission to the Journal.

Conflicts of interest The authors report there are no competing interests to declare.

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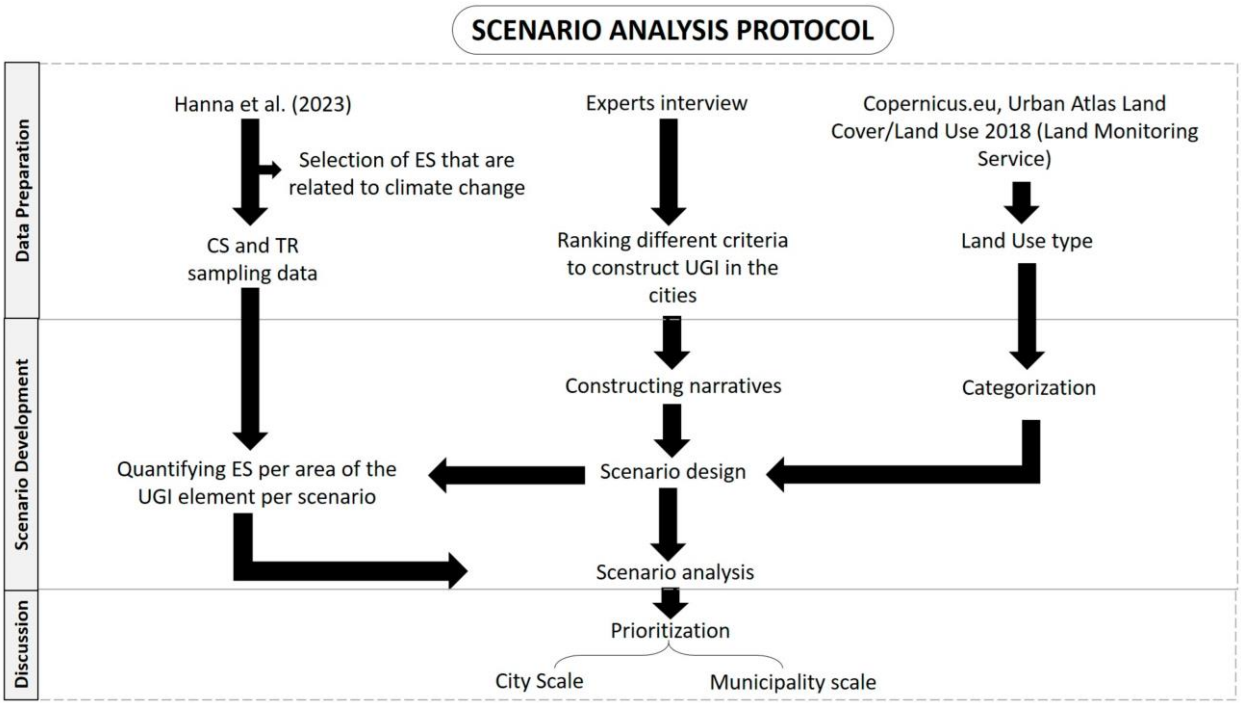

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Scenario Analysis of Green Infrastructure to Adapt Medium-Size Cities to Climate Change: The Case of Zaragoza, Spain

Elie Hanna [1,2], María R. Felipe-Lucia [3] and Francisco A. Comín [2,*]

[1] Departamento de Ciencias Agrarias y del Medio Natural, Escuela Politécnica Superior, Universidad de Zaragoza, 22071 Huesca, Spain; 812719@unizar.es
[2] Instituto Pirenaico de Ecología, Consejo Superior de Investigaciones Científicas-CSIC, 50059 Zaragoza, Spain
[3] Instituto Pirenaico de Ecología, Consejo Superior de Investigaciones Científicas-CSIC, 22700 Jaca, Spain; mariafl@ipe.csic.es
* Correspondence: comin@ipe.csic.es; Tel.: +34-976-369-393 (ext. 880061)

Abstract: Planning a well-structured urban green infrastructure (UGI) is essential for cities to counteract the impacts of climate change. Soil carbon and air temperature differences between open and plant-covered sites were used as proxies of carbon sequestration (CS) and temperature regulation (TR) to evaluate the current conditions of UGI in Zaragoza, a medium-sized city in northeastern Spain. Alternative scenarios were constructed, after a stakeholder consultation, at both city and municipal (city plus peri-urban zone) scales, extrapolating the highest values of CS and TR to two groups of UGI types grouped based on the state of their ecological functioning. We employed analysis of variance to compare mean values of CS and TR across diverse scenarios at both city and municipality scales. Statistically significant differences were found in city-scale and municipality-scale scenarios for both CS and TR. Multiplying CS by area did not show significant variation in city scale. Significant differences were found when multiplying TR by area at both scales, with exceptions in certain scenario combinations. These results suggest favoring the restoration of UGI sites in peri-urban zones (such as forests and steppe zones) to increase CS and those in densely urbanized zones (such as urban parks) to provide TR benefits.

Keywords: urban planning; restoration; adaptation services; nature-based solutions

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1. Introduction

More than half of the world's population today lives in cities, and the urban population of the world is expected to continue growing so that by 2050, 66% of the world's almost 10 billion inhabitants will be urban dwellers [1]. Evidence provided by scientists showed that this rapid urbanization, a major contributor to climate change [2], significantly contributed to deteriorating urban residents' thermal comfort [3]. The worldwide rising of temperatures causes ocean levels to rise, increases the number of extraordinary climate events such as surges, dry seasons, and storms [4], and increases the spread of tropical illnesses [5]. All these have exorbitant impacts on cities' essential services, infrastructure, lodging, jobs, and well-being [6]. Therefore, humans are still dependent on nature for their livelihood [7]. The numerous environmental and social advantages of integrating natural areas into urban and heavily populated areas are becoming more widely acknowledged [8].

Urban green infrastructure (UGI) is a term used to describe systems that incorporate natural elements into the design of a built space, and it includes both green and blue ecosystems [9]. UGI is an essential structural part of cities [10], and all around the world, the creation of a UGI is acknowledged as a crucial instrument in combating climate change [11,12]. UGI is also a useful method for spatial planning in a number of national, regional, and local planning, policy documents, and strategies [13]. For instance, the European Green Belt and the European Green Infrastructure Strategy are good examples [14].

UGI provides benefits that play a key role in climate change adaptation, specifically decreasing the urban heat island effect [15]. These benefits are called ecosystem services (ES), essential for human well-being [16]. ES were classified by the MEA [16] into four groups: supporting services (e.g., soil formation) [17], provisioning services (e.g., food production) [18], cultural services (e.g., spiritual and religious values) [19], and regulating services (e.g., carbon sequestration and temperature regulation) [15,16].

Carbon sequestration is the process of capturing and storing atmospheric carbon dioxide and fixing it in terrestrial structures [20]. It is one method of reducing the amount of carbon dioxide in the atmosphere with the goal of reducing the influence of greenhouse gases on global warming by reducing their increase in the atmosphere [21]. Even though, in 2019, the European Green Deal set an objective to make the EU climate neutral by 2050, few peer-reviewed articles acknowledge local case studies about carbon sequestration in intermediate cities [22]. Temperature regulation is essential in the fight against the impact of heat waves in urban areas. An efficient mitigation of this impact involves introducing different UGI elements in urbanized zones, such as urban parks, urban forests, rooftops, gardened squares, and roundabouts that can play the role of climate cooling shelters [23]. As was demonstrated, these UGI sites should have a high degree of naturalness and functioning and less regularity in their design [9].

Scenario analysis plays a pivotal role in understanding the implications of design choices within UGI for the protection and restoration of ES delivery [24], which has been the subject of constant discussion since the release of the Millennium Ecosystem Assessment [25]. Three processes typically make up a scenario analysis: (1) defining the scope, (2) creating alternative scenarios, and (3) evaluating those scenarios [26]. Scenario analysis has grown in popularity as a method for researching future ecosystems, technologies, societies, climates, and other aspects of the future [27], but it still remains in its early development stages, hence the need for more investigation in this field [24]. It is agreed that scenarios are alternative views of the future that result from a certain set of assumptions and relationships rather than forecasts, projections, or predictions [28]. Through the examination of contrasting scenarios, decision-makers can evaluate various options, recognize possible disadvantages, prioritize areas for restoration, and foresee opportunities, thus facilitating the development of more knowledgeable and robust strategies for UGI planning. This way, one can straightforwardly observe how different scenarios affect the provision of ES [29]. Hence, stakeholder involvement and data-driven analysis are necessary to guarantee that scenario analysis for the provision of ES is reliable and helpful for making decisions [30]. However, research has shown that there is a lack of stakeholder involvement that can represent diverse values [24].

In this paper, we apply these perspectives to the city of Zaragoza, an intermediate-size urban zone in Southern Europe, and its municipality in order to develop a prioritization plan for the improvement of its UGI to counteract the impacts of climate change. The objectives of this paper are to (1) define different scenarios of UGI based on a survey distributed among a range of expert stakeholders, (2) apply the evaluation of ES in different scenarios of UGI within two scales: city and municipality, and (3) analyze the contrasting provision of ES between alternative scenarios of UGI. After this, a prioritization plan based on the potential provision of ES by UGI is proposed. Zaragoza can be a paradigm for other intermediate-size urban zones as it is located in an extremely sensitive location to increased air temperature as a consequence of climate change [31]. We hypothesize that in order to fight against climate change in this type of city, there is a need to work on ES provided by UGI not only on the city scale, where urbanization is high and possibilities of UGI improvement are limited, but also at the municipality scale, where large non-built zones dominate the land cover.

2. Materials and Methods

The protocol for scenario analysis comprises three stages (Figure 1). The first stage of the research consisted of data preparation, which involved ES selection, expert interviews,

and data collection. The second stage consisted of scenario development. It included constructing the narrative, designing the scenario, and quantifying the ES times area (ES × Area) of the UGI element for each scenario based on the data gathered from the first stage. Finally, a prioritization strategy was developed and presented in the discussion section that could be useful for decision-makers to enhance climate adaptation in cities (Figure 1).

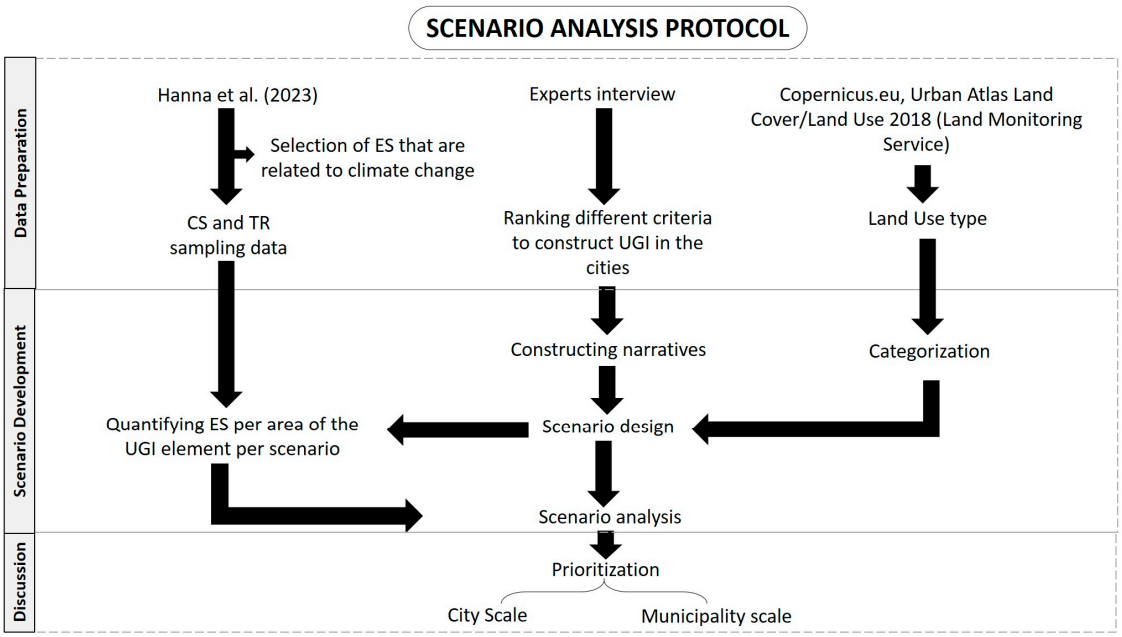

Figure 1. Methodology describing the steps used for the scenario analysis. Ecosystem services (ES), carbon sequestration (CS), temperature regulation (TR), and urban green infrastructure (UGI). Hanna et al. (2023) [9]. Copernicus: https://land.copernicus.eu/ (accessed on 1 October 2023).

2.1. Data Preparation

2.1.1. Study Area and UGI Types

The study area is the city of Zaragoza and its municipality, which is a European medium-sized urban zone with a population of 693,000, a city area of 167 km^2, and a municipality area of 967 km^2. It is situated in the autonomous community of Aragon in northeastern Spain [32]. Zaragoza city lies in the center of the Ebro River Valley, and two tributaries (Gallego and Huerva Rivers) flow out in the Ebro River in the city of Zaragoza (199 m.a.s.l.). Additionally, a big canal carrying water diverted from the Ebro River to irrigate agricultural areas crosses through Zaragoza city. Downtown Zaragoza lies in the surroundings of these waterways, and the outskirts of Zaragoza are located in the upper parts of the old river terraces. More recently, Zaragoza city has been expanding beyond the river terraces throughout the steppe (299 m.a.s.l.), herbaceous, and dry agricultural zones, which conform to the landscape of most of its municipality (Figure 2a).

The natural, semi-natural, and artificial areas that comprise both terrestrial and aquatic ecosystems make up the UGI of Zaragoza. Some of them are tiny spots (urban parks and roundabouts) located in the most densely populated portion of the city. However, most of the comparatively large green spaces, such as riverbanks, forests, and meanders, are located in the peri-urban areas that surround the city. These areas cover a wide range of types of UGI sites and show a high variability of characteristics [9].

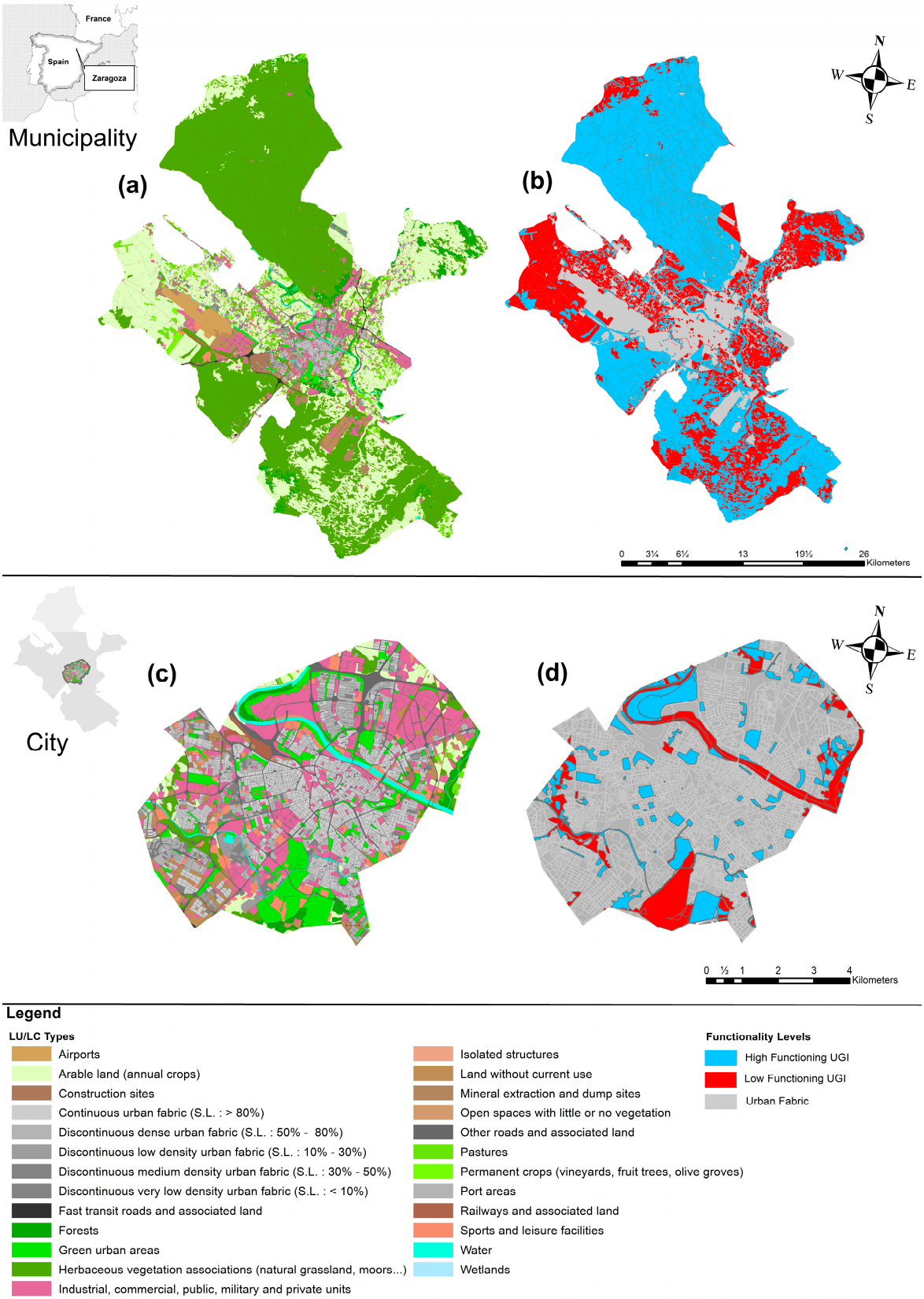

Figure 2. (**a**) LU/LC map of the study area (Zaragoza) at municipality scale. (**b**) Functionality map of urban green infrastructure (UGI) sites of Zaragoza at municipality scale. (**c**) LU/LC map of the study area (Zaragoza) at city scale. (**d**) Functionality map of UGI of Zaragoza at city scale.

2.1.2. Land Use Categorization

The most recent (2018) land cover/land use (LULC) map of Zaragoza was downloaded from Copernicus.eu. We categorized these land use types into three groups based on their characteristics to facilitate a scenario analysis for improving existing UGI sites: (1) Group 1: These areas are already developed or under industrial use. They form the existing urban and industrial landscape and may not be suitable for extensive UGI development without significant transformation. (2) Group 2: This group includes areas that may have lower existing development intensity and have the potential for green improvement. These sites also have high naturalness and ecological functioning. They include pastures, forests, rivers, meanders, and herbaceous and steppe vegetation. (3) Group 3: This group consists of artificial and agricultural zones. They are characterized by low values of ecological functioning. However, they can have a high value of naturalness (e.g., urban parks, squares, and roundabouts) and are located inside the city, such as urban parks, roundabouts, cemeteries, and canals, or peri-urban areas such as agricultural land and arable land (annual cropland). These sites, even if characterized by low ecological functioning, can be crucial for UGI development, providing connectivity, temperature regulation, and enhancing climate change adaptation.

2.1.3. Naturalness and Functioning of UGI Sites

Naturalness is measured as the percentage of area covered by natural components within the UGI site, namely, naturalness = (% of the area with natural components)/10. Hence, naturalness values range from completely natural (10) to entirely artificial (0). For instance, a value of 9 means 90% of the total area of the UGI site is covered by natural components (vegetation). An analogous scale was established to assign values for functioning, which was defined as the degree of natural processes driving the dynamics of the UGI site based on the classical concept of ecosystem functioning. It was measured as the area of the UGI site observed with natural dynamic features (wind and water flows, flooding, erosion, and organic matter accumulation). Therefore, functioning = (% of the area with natural hydro-geomorphological features)/10. The values of functioning also ranged from 0 to 10, with 0 indicating non-functional sites highly influenced by humans and 10 pointing to the complete preservation of natural hydro-geomorphological features and processes. Further details on these two indexes are provided in previous work [33].

2.1.4. Stakeholders Engagement

To enhance decision-making regarding the type of scenario analysis, experts in the fields of urbanism, ecology, law, and politics ($n = 7$) received a semi-structured questionnaire (Appendix A) comprising questions to identify, rank, and rate a number of criteria to prioritize UGI, questions to improve current UGI sites for climate change adaptation, and questions to locate new UGI sites in the city of Zaragoza. The stakeholders were chosen for their dedication to sustainable urban development, which is evident in their involvement in public works, such as contributing to scientific publications and engaging in meetings with Zaragoza residents to gather their ideas and opinions on city development. The selection specifically targeted individuals associated with two organizations that bring together residents, environmental and non-governmental groups, and city officials responsible for managing urban green infrastructure.

2.1.5. Regulating Ecosystem Services

A recent study by Hanna et al. (2023) [9] evaluated and quantified the provision of 8 ESs in UGI sites of the study area (Figure 1). Within the ESs assessed, soil C content and the difference in air temperature between non-vegetated and vegetated zones were used as proxies for carbon sequestration and temperature regulation, which directly link to climate adaptation. Carbon sequestration (CS) is a regulating ES [34]. Soils are a significant carbon sink and have an important role in the fight against climate change [35]. CS values (g of Carbon/m^2) were taken from Hanna et al. (2023) [9]. The methodology of sampling

consisted of taking 3 soil samples, separated 20–200 m from each other, at a depth of 0–20 cm in the vegetated area of 30 UGI sites representing different elements of UGI in Zaragoza. Temperature regulation (TR) is also a regulating ES [36]. In the context of Urban Heat Island, TR in UGI sites is crucial for mitigating the impacts of climate change [37]. TR values (regulated Celsius/m^2) were also derived from Hanna et al. (2023) [9]. Therein, the assessment of temperature regulation (TR) was performed using data loggers (iButton®) installed simultaneously in vegetated and non-vegetated zones and recorded hourly measurements for 1 month during the hot periods of the year (July–August 2022) to assess diurnal variations in air temperature.

2.2. Scenario Development

2.2.1. Scenario Design

The scenario design was performed on two scales: city and municipality. The city scale is represented by the densely populated area;, therefore, it has dense buildings of all types: residential, commercial, and industrial. The city is the central hub of the municipality of Zaragoza. Among the 231 UGI elements found in the city (canals, roundabouts, street trees, rivers, urban forests, university parks, urban natural parks, and green walls), urban parks dominate the landscape of the UGI's artificially constructed sites. The municipality scale represented the peri-urban areas, where the anthropogenic intervention is smaller in comparison with the artificially constructed UGI elements in the city. Therefore, the municipality area covers the city area plus the peri-urban area. The UGI of peri-urban areas consisted of forests, pastures, arable land (annual crop agricultural land), permanent crop agricultural land, steppes (herbaceous mixed land), meander, and rivers. The total number of green infrastructure sites on the municipality scale is equal to 4902.

The scenario design reflected the criteria to plan and build spaces that form the green infrastructure of Zaragoza, which ranked highest among all stakeholders. High and low-functioning UGI sites were differentiated based on the ecological functioning assessment [10], ranking from the minimum 1 to the maximum 10. We created 8 scenarios, 4 for each scale.

City scale: (1) high functioning scenario (HF): current situation of sites with high value of functioning (>5/10) (river, urban natural park, and urban forests). (2) Low functioning scenario (LF): current situation of sites with low value of functioning (<5/10) (urban parks, canals, roundabouts, street trees, university park, and green walls). (3) Improving high functionality scenario (IMHF): improvement (or restoration) of sites with high value of functioning. (4) Improving low functioning scenario (IMLF): improvement (or restoration) of sites with low value of functioning.

Municipality scale: (1) HF = current situation of sites with high value of functioning (>5/10) (river, meander, steppe, forests, and pastures). (2) LF: current situation of sites with low value of functioning (<5/10) (arable land and permanent crops). (3) IMHF = improvement (or restoration) of sites with high value of functioning. (4) IMLF = improvement (or restoration) of sites with low functioning value.

2.2.2. Data Analysis

First, we used the average value of carbon sequestration (CS) and temperature regulation (TR) for similar UGI elements sampled in Hanna et al. (2023) [9]. For instance, for urban parks, we calculated the average of CS and TR for the 13 urban parks sampled (3 samples in each site) and extrapolated these data of CS and TR taken to other urban parks. The same was carried out to different UGI types, where their average value of CS and TR was extrapolated to similar UGI sites with similar characteristics or came under a different name in the LULC map of Zaragoza that was taken from Copernicus.eu. For instance, the steppe is described in the map as having herbaceous vegetation associations. This was assessed for the current situation. For the IMLF and IMHF scenarios, we extrapolated the highest value obtained of CS and TR (not the average) from sites with similar characteristics to other UGI sites exhibiting similar features,

which can be seen as the potential improvement of CS and TR after restoration works. Additionally, we multiplied the value of CS and TR by the area of each site in order to determine the contribution of each UGI element in relation to its size. Then, using the software R, we conducted an analysis of variance (ANOVA) as a statistical method to assess and compare different mean values associated with CS and TR across various scenarios at the city and municipality scale. Using this approach, we found significant differences (or not) related to temperature regulation and carbon sequestration, which improved our comprehension of how these ES are affected by various scenarios and their implications in climate adaptation. However, a significant result in ANOVA does not indicate which specific scenarios are different from each other. For that, we performed post hoc Tukey tests to conduct pairwise comparisons and identify where these differences lie. This method, which combines ANOVA and post hoc Tukey testing, improved the accuracy and comprehensiveness of our statistical studies by providing a more complete picture of the connections between CS, CS × Area, and TR and TR × Area under various scenarios.

In order to determine which group of UGI sites provided the most CS and TR delivery per type, we plotted bar charts that compared CS and TR delivery across different UGI types for the improvement scenarios at the municipality and city scales. Additionally, to understand what UGI element occupied the most area, we constructed bar charts that summed up the area of UGI sites that belong to the same type to compare it to other types. Finally, to understand which group of UGI sites belong to the same type, providing the largest area and the most CS or TR delivery, we plotted bar charts that summed up CS × Area and TR × Area per type.

Additionally, to prioritize restoration efforts in relation to the requirements and contributions of each scale, we developed priority maps using ArcGIS that could be useful tools for policymakers and urban planners. These tools offer a visual representation of spatial data, assisting in directing their efforts, the efficient allocation of resources, and the making of decisions [38].

3. Results

3.1. Study Area and UGI Types

In the municipality as a whole, pastures represented the highest percentage of the area as UGI sites at 37.5%, followed by forests at 26.9%, which constituted a relatively high percentage of the area. Additionally, rivers showed a lower percentage, at 9.32%, followed by herbaceous vegetation associations at 6.59%. Permanent crops accounted for 4.39%, urban parks 4.08%, and arable land 3.87%. The UGI elements occupying smaller areas were urban forests at 2.37%, meanders at 1.95%, and canals at 1.49%. This was followed by lower percentages of cemeteries at 0.766%, wetlands at 0.317%, urban natural parks at 0.242%, squares at 0.0805%, community gardens at 0.0619%, street trees at 0.0438%, and roundabouts at 0.0134%. The smallest percentage was represented by green walls at 0.00083% (Figure S1a).

At the city scale, urban parks were the dominant UGI type, representing 36.7% of the total area of UGI elements, followed by rivers at 27.5% and urban forests at 18.5%. Smaller percentages of cemeteries were found, constituting 5.61% of the UGI elements, followed by forests at 2.97%, canals at 2.80%, and pastures at 2.16%. The UGI that occupied the smallest area at the city scale was urban natural parks at 1.88%, followed by squares at 0.628%, community gardens at 0.345%, street trees at 0.342%, arable land at 0.232%, herbaceous vegetation associations at 0.155%, and roundabouts at 0.104%. The lowest use was green walls at 0.006% (Figure S1b).

Pastures and forests are therefore the dominant UGI types in peri-urban area, occupying 35, 34% (37.5–2.16%), and 23, 93% (26.9–2.97%), respectively.

3.2. Regulating Ecosystem Services

The findings show temperature regulation (TR) and carbon sequestration (CS) values for all UGI types in the current and improved scenario (Table 1). For CS, urban forests emerged as notable contributors, representing a current state value of 0.048 g C/m^2, which increased to 0.058 g C/m^2 in the improved scenario. Herbaceous vegetation associations and pastures came after, with a value of 0.020 in the current situation, jumping to 0.042 in the improved situation. Urban natural parks located in the city doubled their value in the improved scenario to 0.04. Similarly, the value of CS in urban parks increased substantially from 0.019 in the current state to 0.037 in the improved state. This was followed by meanders increasing from 0.025 to 0.032 in the improved scenario. Forests also increased modestly from 0.017 to 0.018, and canals from 0.011 to 0.018. As for street trees, they had a value of 0.015 g C/m^2 in the current state, which jumped to 0.017 in the improved state. Squares increased to 0.015 in the improved scenario from 0.010 in the existing situation. In the present state, arable lands had a value of 0.012 g C/m^2. In the improved state, that value increased to 0.015 g C/m^2. Community gardens and permanent crops presented a value of 0.012 (0.015 in the improved scenario). Rivers and cemeteries had a value in the current situation of 0.009 and 0.01, respectively, which increased to 0.012 in the improved scenario. Finally, the value of CS for the roundabout doubled, from 0.005 in the current state to 0.01 in the improved scenario.

Table 1. Values of carbon sequestration (CS, gram of Carbon/m^2) and temperature regulation (TR, °C/m^2) for the current and improved scenario for different elements of urban green infrastructure. Diff stands for the difference between each value of CS in the current conditions and CS in the improved scenario (CS improved–CS current), and also between TR in the current conditions and TR in the improved scenario (TR improved–TR current).

Type	Abbreviation	Functioning	CS	CS Improved	Diff	TR	TR Improved	Diff
Canal	C	Low	0.011	0.018	0.007	0.579	2.514	1.935
Square	S	Low	0.010	0.015	0.005	0.814	1.832	1.018
Pastures	P	High	0.020	0.042	0.022	1.022	1.100	0.078
Meander	M	High	0.025	0.032	0.007	1.155	1.492	0.337
Urban Park	UP	Low	0.019	0.037	0.018	0.341	1.331	0.990
Street trees	ST	Low	0.015	0.017	0.002	0.388	1.100	0.712
River	R	High	0.009	0.012	0.003	0.618	1.100	0.482
Herbaceous vegetation association	H	High	0.020	0.042	0.022	1.022	1.100	0.078
Cemetery	CE	Low	0.010	0.012	0.002	0.254	0.950	0.696
Permanent crop	PC	Low	0.012	0.015	0.003	0.400	0.660	0.260
Forest	F	High	0.017	0.018	0.001	0.586	0.700	0.114
Community garden	CG	Low	0.012	0.015	0.003	0.400	0.660	0.260
Roundabout	RB	Low	0.005	0.010	0.005	0.398	0.511	0.113
Arable land	AR	Low	0.012	0.015	0.003	0.425	0.500	0.075
Urban forest	UF	High	0.048	0.058	0.010	0.275	0.468	0.193
Urban natural Park	UNP	High	0.020	0.040	0.020	0.120	0.400	0.280

As for TR, canals, with a value of 0.579 °C/m^2 in its current state, exhibited a substantial increase to 2.514 °C/m^2 in the improved scenario. Next, squares increased to 1.832 in the improved state (0.814 in the current situation). The value of TR in meanders improved modestly, from 1.115 in the current situation to 1.492 in the improved situation. For urban parks, the value increased substantially from 0.256 to 1.331 in the improved situation. Street trees, rivers, herbaceous vegetation associations, and pastures came after with values of 0.388, 0.618, 1.022, and 1.022 in the current situation, jumping to 1.1 in the improved situation. Subsequently, cemeteries had a value of 0.0254 in the current state, jumping to 0.95 in the improved state. Forests, with a value of 0.586 in the present state, increased to 0.7 in the improved scenario. Community gardens and permanent crops presented a value of 0.4 compared to 0.66 in the improved scenario. Moreover, concerning the value of TR for roundabouts, it increased to 0.511 in the improved situation. Likewise, the value for arable land increased to 0.5 (0.425 in the present situation). Finally, urban forests and urban natural parks came after with values of 0.275 and 0.12, which increased to 0.468 and 0.4, respectively, making urban natural parks the lowest contributors in terms of temperature regulation (Table 1) (Figure S2).

3.3. Scenario Design and Data Analysis

At the city scale, for CS, a one-way ANOVA revealed that there was a statistically significant difference in mean between the different types of scenarios (p-value < 0.001; Figure 3). However, when multiplying the CS by area, no significant difference was found (p-value = 0.498) (Table 2). Tukey's post hoc test for CS found that the mean value was significantly different between all different scenarios ($p < 0.05$). Tukey's post hoc test cannot be applied for CS × Area because ANOVA already proved that there was no significant difference.

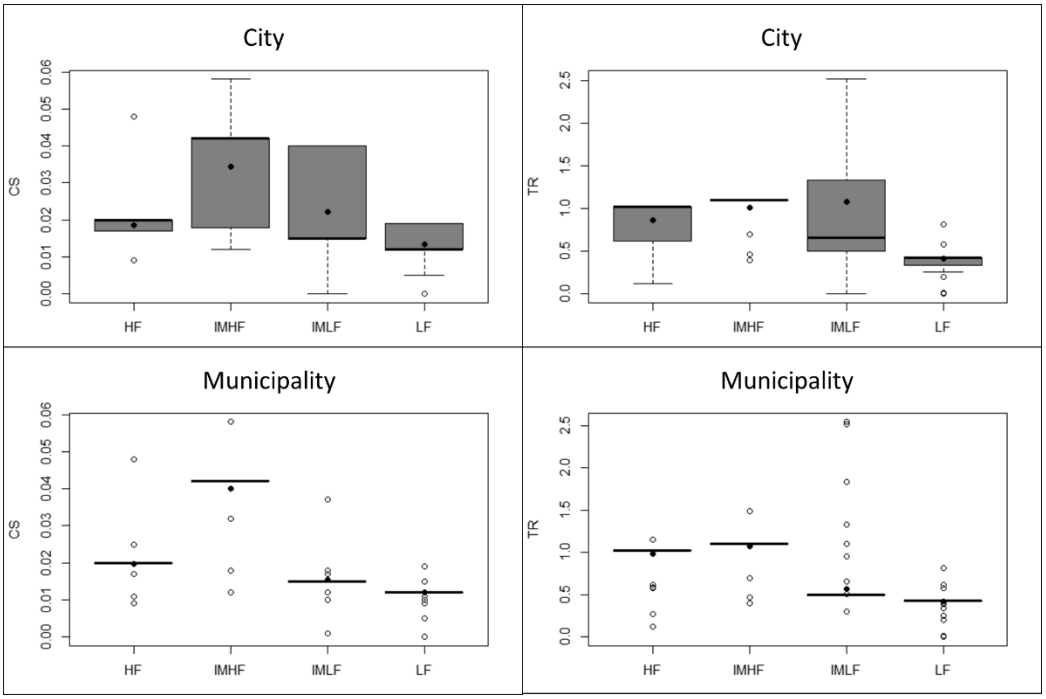

Figure 3. One-way ANOVA comparing the delivery of carbon sequestration (CS) and temperature regulation (TR) under four types of scenarios. LF: current state of low functioning sites. HF: current state of high-functioning sites. IMLF: improvement/restoration scenario of low-functioning sites. IMHF: improvement/restoration scenario of high functioning sites at city and municipality scale. Hollow dots represent outliers. Black dots represent the mean value.

Table 2. *p*-values for ANOVA for different types of scenarios, LF (current situation of sites with low value of functioning), HF (current situation of sites with high value of functioning), IMLF (improvement of sites with low value of functioning), and IMHF (improvement of sites with high value of functioning), for carbon sequestration (CS). CS × Area, temperature regulation (TR), and TR × Area for the city and municipality scale, as well as the *p*-value for the post hoc tests between different scenarios for the city and municipality scale. Diff stands for the difference between the means (* stands for significant (*p*-value < 0.05). N/A stands for non-available).

CITY	**ANOVA**	**ES/ES × Area**	**CS**		**CS × Area**		**TR**		**TR × Area**	
		***p*-value**	**2.00×10^{-16} ***		**0.498**		**2.00×10^{-16} ***		**0.0149 ***	
	POST-HOC	Scenario comparison	Diff	*p*-value	Diff	*p*-value	Diff	*p*-value	Diff	*p*-value
		IMHF-HF	0.0158	2.00×10^{-16} *	N/A	N/A	0.145	0.105	18,519.069	0.556
		IMLF-HF	0.0036	0.0172 *	N/A	N/A	0.221	0.0007 *	13,065.233	0.732
		LF-HF	−0.0053	0.0001 *	N/A	N/A	−0.447	2.00×10^{-16} *	−16,962.728	0.540
		IMLF-IMHF	−0.0122	2.00×10^{-16} *	N/A	N/A	0.076	0.548	−5453.836	0.973
		LF-IMHF	−0.0211	2.00×10^{-16} *	N/A	N/A	−0.592	2.00×10^{-16} *	−35,481.797	0.027 *
		LF-IMLF	−0.0089	2.00×10^{-16} *	N/A	N/A	−0.668	2.00×10^{-16} *	−30,027.961	0.035 *
MUNICIPALITY	**ANOVA**	**ES/ES × Area**	**CS**		**CS × Area**		**TR**		**TR × Area**	
		***p*-value**	2.00×10^{-16} *		2×10^{-16} *		2.00×10^{-16} *		2×10^{-16} *	
	POST-HOC	Scenario comparison	Diff	*p*−value	Diff	*p*−value	Diff	*p*−value	Diff	*p*−value
		IMHF-HF	0.020	2.00×10^{-16} *	247.295	0.0000001 *	0.085	2.00×10^{-16} *	2745.848	0.152
		IMLF-HF	−0.004	2.00×10^{-16} *	−249.110	0.0000082 *	−0.422	2.00×10^{-16} *	−10,681.095	2.00×10^{-16} *
		LF-HF	−0.008	2.00×10^{-16} *	−284.250	0.0000002 *	−0.562	2.00×10^{-16} *	−13,685.891	2.00×10^{-16} *
		IMLF-IMHF	−0.024	2.00×10^{-16} *	−496.404	2.00×10^{-16} *	−0.507	2.00×10^{-16} *	−13,426.944	2.00×10^{-16} *
		LF-IMHF	−0.028	2.00×10^{-16} *	−531.544	2.00×10^{-16} *	−0.647	2.00×10^{-16} *	−16,431.740	2.00×10^{-16} *
		LF-IMLF	−0.003	2.00×10^{-16} *	−35.140	0.930	−0.140	2.00×10^{-16} *	−3004.796	0.298

Likewise, a one-way ANOVA for TR revealed that there was a statistically significant difference in mean between the different types of scenarios (*p*-value < 2×10^{-16}). Contrary to CS × Area, the ANOVA for TR × Area exhibited a significant difference (*p*-value = 0.0149). Tukey's post hoc test for TR found that the mean value was not significantly different from IMHF–HF (*p*-value = 0.105) and IMLF–IMHF (*p*-value= 0.548) but was significantly different for all other scenarios ($p < 0.05$). Tukey's post hoc test for TR × Area revealed that there was a statistically significant difference in mean only for LF–IMHF (*p*-value-0.027) and LF–IMLF (*p*-value = 0.035). For the rest, there was no significant difference (Table 2) (Figure S3).

At the municipality scale, for CS, a one-way ANOVA revealed that there was a statistically significant difference in mean between the different types of scenarios (*p*-value < 2×10^{-16}) (Figure 3). The same thing happened when multiplying the CS by area, and a significant difference was found ($p < 2 \times 10^{-16}$). Tukey's post hoc test for CS found that the mean value was significantly different from all different scenarios ($p < 0.05$). As for CS × Area, the post hoc revealed that there was no significant difference except for the LF–IMLF scenario (*p*-value = 0.93). For the rest, there were significant differences (Table 2).

The ANOVA for TR revealed that there was a statistically significant difference in mean between the different types of scenarios (*p*-value < 2×10^{-16}). The same thing happened when multiplying the TR by area, and a significant difference was found ($p < 2 \times 10^{-16}$). Tukey's post hoc test for TR found that the mean value was significantly different between all different scenarios ($p < 0.05$). Tukey's post hoc test for TR × Area revealed that there was no significant difference in mean except for HF–IMHF (*p*-value = 0.152) and LF–IMLF (*p*-value = 0.298). For the rest, there was a significant difference (Table 2) (Figure S3).

4. Discussion

4.1. Typology of the UGI

The results highlighted the landscape difference between the urban and peri-urban areas. In particular, they show that peri-urban areas are dominated by sites with high ecological functioning, while urban areas are dominated by low-functioning green zones because these urban green areas were constructed mostly as recreational hubs to contribute to the overall well-being of urban residents [39]. Additionally, the presence of natural ecosystems, such as rivers in this city, holds ecological importance. Rivers and their riparian areas, being high-functioning sites, provide a habitat for diverse flora and fauna [40] that can counter-balance the low functioning of more artificial sites, such as urban parks. Hence, there is an important need for the conservation and careful restoration of these rivers and their riparian zones, as well as other natural sites, in order to balance human needs and environmental conservation in the city [41].

4.2. Insights into Carbon Sequestration and Temperature Regulation at City and Municipality Scales

Overall, the restoration scenarios showed positive trends in both carbon sequestration and temperature regulation for various UGI types. At the city scale, a statistically significant difference in carbon sequestration among scenarios was observed. However, when considering carbon sequestration by area, the difference became non-significant. These findings reveal that improving carbon sequestration under improved scenarios is not influenced by the area of the UGI site but by the type of the green infrastructure site. For instance, for climate adaptation, city planners should think cost-effectively. They should focus on restoring and conserving urban green sites with high carbon sequestration potential, such as urban forests, as they act as carbon sinks inside the city [42], instead of wasting resources on restoring lower-performing sites such as roundabouts. Another approach is to imitate the complexity of urban forests by planting different species with different numbers of strata when designing new urban green zones. This sheds light on the importance of our approach and could lead policymakers to decide where to prioritize their efforts for the restoration and conservation of urban green infrastructure.

Regarding temperature regulation at the city scale, there was a statistically significant difference in mean between the different types of scenarios. Contrary to CS × Area, the ANOVA for TR × Area showed significant differences. Tukey's post hoc test for TR found that the mean value was not significantly different between the scenario of the current state of high-functioning sites and the scenario of improving high-functioning sites. Similarly, there is no significant difference between the scenarios of improving low-functioning sites and improving high-functioning sites. These findings suggest that the impact of urban planning interventions may not be significantly different for high-functioning urban green infrastructure sites if planned only to reach the maximum TR observed currently. However, such was not the case for low-functioning sites because there were statistically significant differences only between the scenario of the current state of low-functioning sites and the scenario of improving high-functioning sites, analogously between the scenario of the current state of low-functioning sites and the scenario of improving low functioning sites. These significant differences suggest that there are meaningful changes in temperature regulation outcomes when transitioning from the current state of low-functioning sites to either improving high-functioning sites or improving low-functioning sites. Hence, decision-makers should propose restoration strategies that involve restoring low-functioning sites or even improving the functioning of low-functioning sites. This is in good agreement with previous studies highlighting the cooling effects of urban parks (low-functioning UGI sites) in assisting urban planning and decision-makers in mitigating the urban heat island effect and improving urban sustainability [43,44]. Other low-functioning UGI sites have the same importance. For instance, street trees, as urban green infrastructure sites with low functioning values, play an important role in temperature regulation in cities,

presenting cooling refuges, providing shading for the citizens, and playing a role in the evapotranspiration process, which can help in cooling their surroundings [45].

At the municipality scale, for CS, there was a statistically significant difference in mean between all different types of scenarios. The same thing happened when multiplying the CS value by area, and a significant difference was found. As for CS × Area, there was no significant difference between the scenario of current low-functioning sites and improving low-functioning sites scenario. This suggested that carbon sequestration is not only influenced by the total amount of carbon accumulated but also by the area and distribution of UGI across the municipality. Additionally, the results indicated that when multiplying CS by area, the carbon sequestration of the scenarios of restoring low-functioning sites is statistically similar to the current state of low-functioning sites. Therefore, at a municipality scale, policymakers should focus their efforts on restoring and conserving high-functioning sites, as it has been proven that restoring these green zones is a winning strategy for storing carbon. Moreover, restoring the ecological functioning of those UGI sites, where it is still possible, would increase carbon sequestration. The results are consistent with previous studies, showing the importance of managing and restoring high-functioning sites (such as forests) due to their significant role in absorbing carbon and mitigating climate change [46,47]. As for temperature regulation, at a municipal scale, the results showed that the restoration scenarios were only effective in regulating temperature but inefficient in doing so relative to their area. Hence, policymakers and urban planners are encouraged to explore other factors, such as vegetation density, local climate conditions, the location of green sites, and the role of these green zones (green corridors connecting the peri-urban to the urban) that could influence the regulation of temperature at municipality scale, especially in peri-urban areas where the results of restoration of TR × Area in the city are significant. However, it is important to note that in peri-urban areas, the impact of individual UGI sites on temperature regulation could be localized, providing cooling effects to the immediate surroundings, because there are few people living in these areas. Thus, it has less importance except in the case that these green zones are strategically planned and interconnected (corridors and patches), which can result in landscape connectivity, producing a combined influence contributing to the reduction of urban heat islands [48].

4.3. The Importance of Peri-Urban Areas

Comparing the city scale and municipality scale (city + peri-urban areas) has shown that the green infrastructure in peri-urban zones has an important role in the provision of ecosystem service. Our study has proved that UGIs in peri-urban areas are big areas that tend to show higher capacities for carbon sequestration compared to their city counterparts. These vast lands not only facilitate the growth of more complex vegetation but also enable the development of ecologically diverse landscapes, causing increased carbon absorption and storage [49]. The results are in line with previous studies, highlighting the importance of maintenance and restoration of large functional UGIs dominated by natural processes, dynamics, and structures that display permeable surfaces and undisturbed hydro-morphology that can threaten the livability of urban areas in the short term as a consequence of global warming [9,50]. These peri-urban zones can play a crucial role in mitigating climate change by acting as valuable carbon sinks [51]. Additionally, they offer a diversity of urban green infrastructure elements that are not present in the city, such as pastures [52], where soils under a range of pasture types have considerable potential for sequestration of atmospheric CO_2. Furthermore, the magnitude of this potential can be greatly modified by pasture management practices [53].

Forests were another type of green infrastructure dominant in the peri-urban area of Zaragoza. They can play a large role in climate change through the sequestration of carbon through biological growth, which can increase carbon fixation. Carbon is captured not only in tree biomass but mostly in forest soils [54]. Management practices for enhancing soil C stock in forests consist of careful site preparation, adequate soil drainage, growing species with a high net primary production, applying N and micronutrients (Fe) as fertilizers or biosolids, and conserving soil and water resources [55]. However, forest restoration should not be performed in other types of habitats, such as steppe zones, because the latter have intrinsic features and provide specific ecosystem services (e.g., they harbor a highly valued specific biodiversity, both plant and animal communities, based on gypsum soils).

In addition, the steppe (herbaceous vegetation associations) zones of Zaragoza, occupying large areas in the north and south peri-urban zones, are highly covered by herbaceous vegetation associations. Despite their seemingly harsh conditions, they possess extensive root systems that play a crucial role in storing carbon below the ground, thus having high sequestration potential [56–58]. However, herbaceous vegetation cannot provide TR, like forests do, because of its low height and density compared to tree associations.

Thus, the peri-urban areas of Zaragoza consist of a great variety of UGI types, which, if adequately restored and connected, have the potential to contribute high CS net values that could help to address the challenges of climate change. Such is not the case for the highly urbanized zones of Zaragoza.

4.4. Priority Analysis

Providing temperature regulation by urban green infrastructure sites had a direct impact on the city scale due to the need for cool and shade refuges for citizens in the face of heat [59]. However, on the municipality scale, carbon sequestration is most significant due to the importance of peri-urban areas contributing as carbon sinks to reduce the effect of climate change [51]. In terms of temperature regulation, urban parks and rivers have the highest priority for restoration, so urban planners and decision-makers should focus on restoring the riparian areas of the rivers and restoring parks through revegetation and providing comfortable shelters. These areas have a high potential to be climate refuges, especially in the hot summer weather of Zaragoza [60], due to their dominant presence in the city (Figure S4). This is followed by urban forests, canals, and cemeteries. It is important to restore and preserve these areas as they come in second place in priority (Figure S4). The other 13 types are of less importance in terms of carbon storage.

We recommend decision-makers follow the Pareto principle that states that roughly 80% of outcomes (temperature regulation) come from 20% of causes (urban green infrastructure sites) [61] when allocating resources for restoring urban green infrastructure to fight climate change in the city. In our case, restoring the elements of the urban green infrastructure of first and second priority, which represents 27.7% of the total area of UGI, could be enough to produce an 80% outcome of temperature regulation. However, decision-makers do not have to restore all elements of urban green infrastructure, i.e., all types (Figures 4 and S4).

Priority analysis also showed that the highest restoration priority goes to pastures due to their large area and their capacity for carbon intake. Forests and steppes (herbaceous vegetation associations) come second in priority. All are high-functioning green infrastructure sites. Hence, the importance of these sites cannot be neglected. We recommend decision makers focus their efforts on restoring and conserving these areas as they present high potential in storing carbon in the soil and thus maintain a balance with the potential pollution that comes from the city (Figures 4 and S4).

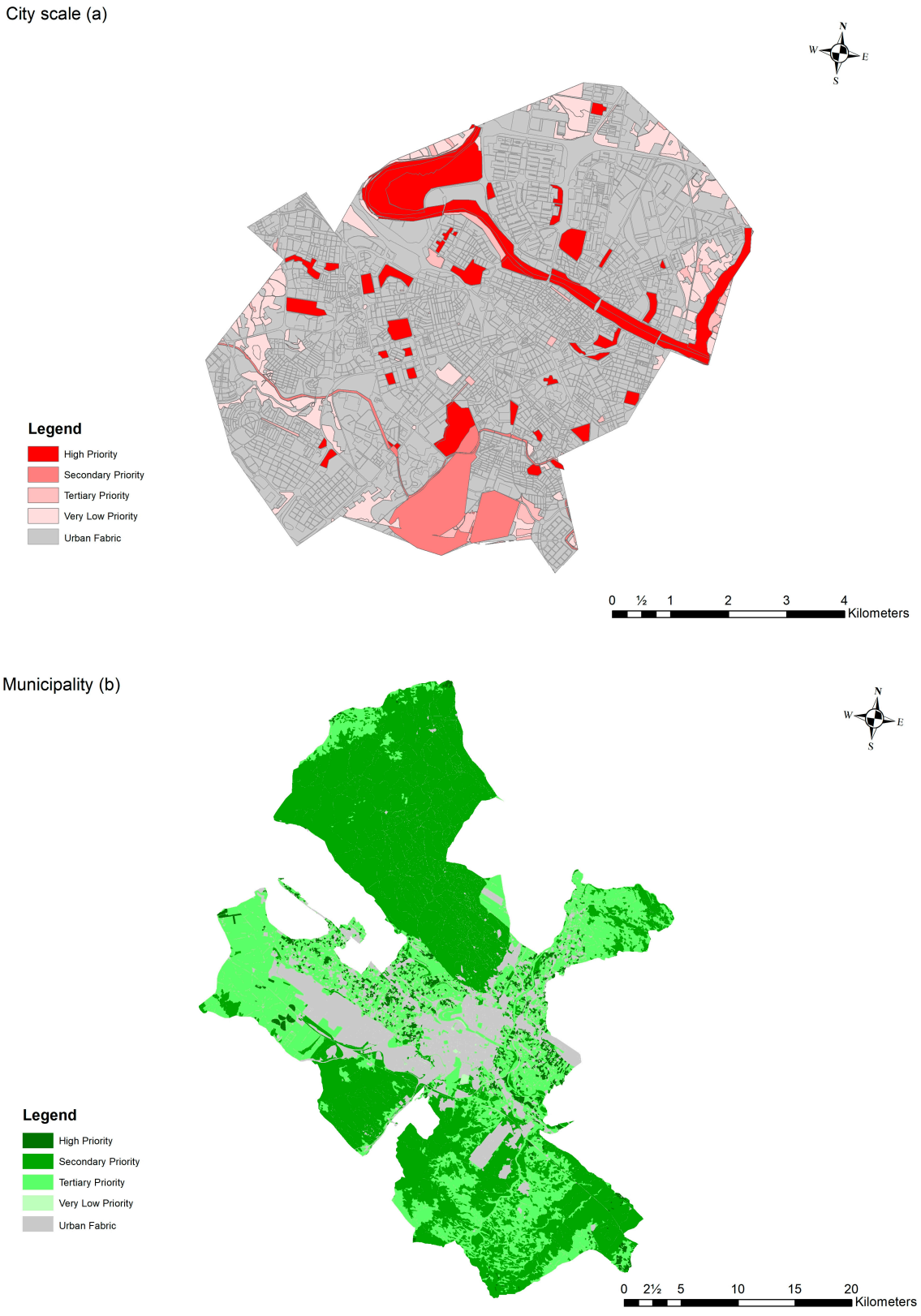

Figure 4. (**a**) Priority map of restoration for temperature regulation (TR) in the city. (**b**) Priority map of restoration for carbon sequestration (CS) in the municipality.

4.5. Contribution to a Climate Neutral Municipality

According to the European Union (https://research-and-innovation.ec.europa.eu accessed on 18 November 2023), cities play a pivotal role in achieving climate neutrality by 2050, the goal of the European Green Deal. They take up only 4% of the EU's land area, but they are home to 75% of EU citizens. Furthermore, cities consume over 65% of the world's energy and account for more than 70% of global CO_2 emissions. In this study, the results showed that there is no significant difference when we multiply the value of carbon sequestration by area in the improved scenario on a city scale. So, new UGI areas could be required to achieve a significant impact and contribute to the climate neutrality of a European city like Zaragoza, Spain. We raised two questions: supposing that the restoration scenarios are already in place in the city, how much area is required to improve carbon sequestration delivered by UGI in cities by 50%? Additionally, can policymakers find space to build these areas? To answer the first question, we calculated the area needed for the different percentages of CS increase.

$$Area\ (for\ 50\%\ increase\ of\ CS) = \frac{\sum(area\ of\ UGI\ elements\ in\ the\ city) \times 0.5 \times \sum(CS\ in\ city)}{\sum(CS\ in\ city)},$$

$$Area\ (for\ 50\%\ increase\ of\ CS) = \sum(area\ of\ UGI\ elements\ in\ the\ city) \times 0.5$$

$$Area\ (for\ 50\%\ increase\ of\ CS) = 4,603,038.90 \text{ square meters}$$

The LU/LC map showed that there is land without current use with a total area of 2,591,334.30 m^2 (Figure S5), if we suppose that the municipality can interfere and build new UGI elements on these sites. If so, it will achieve a 28.14% (not 50%) increase in the carbon sequestration provided by the UGI elements in the city, helping Zaragoza city to reach their objective to be a neutral city by 2030 (Figure S6). We also recommend that city planners design UGI elements with high functioning in these lands according to the biogeographic location of the site. In any case, it was demonstrated that high-functioning sites are efficient in storing carbon in the soil.

4.6. Value and Limitations of the Approach

In this paper, we aimed to contribute to filling the gap in research on the subject of ecosystem services and climate adaptation strategies in medium-sized cities [62]. Many investigations studied the potential of greeneries to mitigate urban heat islands and greenhouse gas emissions through carbon storage [63–65]. However, to the best of our knowledge, a comparative study assessing carbon sequestration and temperature regulation separately in relation to climate adaptation of urban zones is lacking. To make informed decisions about the restoration strategies for the improvement of UGI, it is important to know which types of sites can provide better carbon accumulation and regulate air temperature, the two most relevant ESs to buffer climate change impacts.

The presented approach allows us to prioritize restoration at a municipality and city scale, selecting areas according to their CS and TR capacities in the face of climate change. The majority of restoration research was planned at the ecosystem scale, with reference ecosystems being used to define restoration operations and success [66]. Restoration plans based on the provision of multiple ES at the territory scale are an innovative approach [67]. In order to determine the zones where high values of services are present, which increases the significance of the selected zones, the evaluation of various ESs is based on the location of the UGI sites that provide these two ESs.

Focusing restoration efforts not only at the city scale but also at a larger scale is important for addressing the intricate challenges of environmental conservation and climate resilience [68]. While working on a city scale provides an easy and direct perspective on urban health [69], working on a larger scale allows for a more global approach. Hence, broadening the perspective could be cost-effective in the long term and reveal hidden information and mechanisms that urban planners might have neglected [70]. For instance, they might design restoration strategies for urban parks only dominant on the city scale (not present in peri-urban areas). If decision-makers provide targeted restoration measurements for urban parks that have specific characteristics and neglect the other types of urban green infrastructure dominantly present in peri-urban areas, such as pastures that play an important part in carbon sequestration, they could be wasting resources. Thus, our approach ensures a comprehensive and informed restoration strategy for policymakers, decision-makers, and urban planners, optimizing environmental benefits and resource utilization in the context of climate adaptation.

Although our approach to scenario analysis of green infrastructure delivery of ecosystem services to reduce the impact of climate change is robust and strategic, it is important to recognize that it has certain limitations. One important factor is that the spatial data used may become outdated with time, and the effectiveness of interventions can be influenced by future urban developments. For instance, in our approach, we used an LU/LC map from Copernicus dated 2018. Changes in land use and land cover may have occurred, though not drastically. Additionally, the LU/LC map does not differentiate between the different types of UGI in the city. Therefore, we had to use the data of UGI sites that were studied by Hanna et al. (2023) [33], which evaluated UGIs in Zaragoza. Furthermore, our approach focused primarily on the ESs of TR and CS. Other ecosystem services, such as water regulation [71] and habitat biodiversity [72], could also contribute to climate adaptation. Further investigation is required to study the scenario analysis of other ecosystem services provided by urban green infrastructure and their relation to climate change adaptation and urban planning. This approach could also be combined with other UGI characteristics of interest, such as connectivity between sites, which can be relevant for the contribution of UGI to buffer climate change.

5. Conclusions

The UGI of Zaragoza was mostly characterized by low functioning sites located in the densely urbanized area of the city. High-functioning UGI sites were located in the peri-urban area of the city. A similar pattern was found in other European cities [73]. Therefore, the methodology proposed here for the restoration of UGIs could be applicable in other medium-sized cities.

Scenario analysis based on ecosystem services is a useful tool for predicting the impact of restoration measurements to fight against climate change in urban zones. Restoring high ecological functioning green infrastructure sites (forests, steppes, and riparian areas) in peri-urban zones is of high importance. This will improve the provision of carbon sequestration due to the increase of both the carbon sequestration rate and the area of available sites. However, in densely built zones, the provision of carbon sequestration will not improve because of the generalized lack of large areas of sites with good ecological functioning. Temperature regulation will increase in both city and peri-urban zones after restoration. However, it is recommended to restore green infrastructure sites for temperature regulation in densely populated zones because of their direct benefit to more inhabitants. This presented research makes a significant contribution to the growing body of literature in the field of adapting to climate change. It maximizes environmental benefits and resources, helping urban planners and policymakers prioritize UGI sites to address carbon accumulation and temperature regulation within the context of climate adaptation.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/land13030280/s1, Figure S1: (a) Percentage of the sum of the area of each UGI element at the municipality scale. (b) Percentage of the sum of the area of each UGI element at the city scale. Figure S2: (a) Carbon sequestration (CS) of each UGI element. (b) Temperature (TR) of each type of UGI site. Figure S3: Post hoc test showing the means and the difference in means levels of different types of scenarios for carbon sequestration (CS), CS × Area, temperature regulation (TR), and TR × Area for the municipality scale and city scale. LF (current situation of sites with low value of functioning), HF (current situation of sites with high value of functioning), IMLF (improvement of sites with low value of functioning), and IMHF (improvement of sites with high value of functioning). Figure S4: (a) Priority analysis of restoration for temperature regulation (TR) by area in the city and sum of TR × Area (°C). (b) Priority analysis of restoration for carbon sequestration (CS) by area in the municipality. Sum of CS × Area (g). Figure S5: Map of land without current use in the city, where new urban green infrastructure sites could be designed by the municipality of Zaragoza to increase carbon storage in the city. Figure S6: Graph showing the area needed to improve carbon sequestration delivered by UGIs in cities by 1%, 5%, 10%, 20%, 30%, 40%, and 50%.

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Appendix A

Questionnaire on criteria for improving and creating green infrastructure in the city of Zaragoza to adapt to climate change (Translated from Spanish).

Green infrastructure refers to all types of spaces with natural components (soil, vegetation, and water) and artificial components (spaces for recreation, shows, and rest), including aquatic spaces, which provide environmental services for the human population (e.g., carbon accumulation, wind or flood buffering, and recreation) and are subject to natural processes (water flows, connection with water channels, wind erosion, etc.) or artificial processes (garbage and leaf litter cleaning, irrigation, planting, etc.).

The objective of this survey was to obtain the opinion of experts and stakeholders on the characteristics and spatial distribution that the green spaces of Zaragoza should have to mitigate the effects of climate change.

The study focuses on green spaces larger than 1 ha, excluding those with highly artificial morphology, such as streets with tree alignments. The following table includes various criteria for planning and building spaces that form Zaragoza's green infrastructure with the aim of mitigating the impacts of climate change and adapting the city to these changes.

Criteria	Definition	Ranking (0–10)	Rating (0–100%)
Naturalness and functioning	Naturalness: percentage of surface covered with natural components (soil, vegetation, water). Functioning: percentage of surface subject to natural processes (water flows, accumulation and decomposition of leaf litter contributing to soil formation).		
Cultural use	Contribution of the site to recreational functions (games, concerts, shows, entertainment) enjoyed by the population.		
Economic cost	Expenses associated with maintaining or building a green space		
Biodiversity	Capacity to harbor biodiversity		
Potential users	Population density around the green space		
Connectivity	Degree of connectivity between the different green spaces		
Size	Surface area occupied by the green space		

Question 1: Review the list of criteria from the previous table and add or remove criteria as you consider them interesting or important for planning and building green spaces that form the green infrastructure network of the city of Zaragoza.

Please write them in the first column of the table and define them in the second column.

Question 2: Rate from 0 to 10 the importance of each green infrastructure criterion for mitigating the effects of climate change or adapting to them in the city of Zaragoza, with 10 being the highest value and 0 being the lowest.

Write your evaluation (including decimals if you consider it appropriate) in the third column of the table (Ranking).

Question 3: In the fourth column (Rating), distribute 100 points among the criteria in the table so that the total adds up to 100%. That is, if one criterion is assigned 100%, the other criteria should be assigned 0%; or if one criterion is assigned 50%, then the remaining 50% will be distributed among the other criteria.

Question 4: Which option from the following list do you consider most suitable for mitigating the effects of climate change in Zaragoza? Mark with a cross your preferred option (only one response)

- ○ Leave the green spaces as they are because they are already sufficient in number and extent;
- ○ Improve existing green spaces;
- ○ Create new green areas;
- ○ Both improve existing ones and create new ones;
- ○ Other:

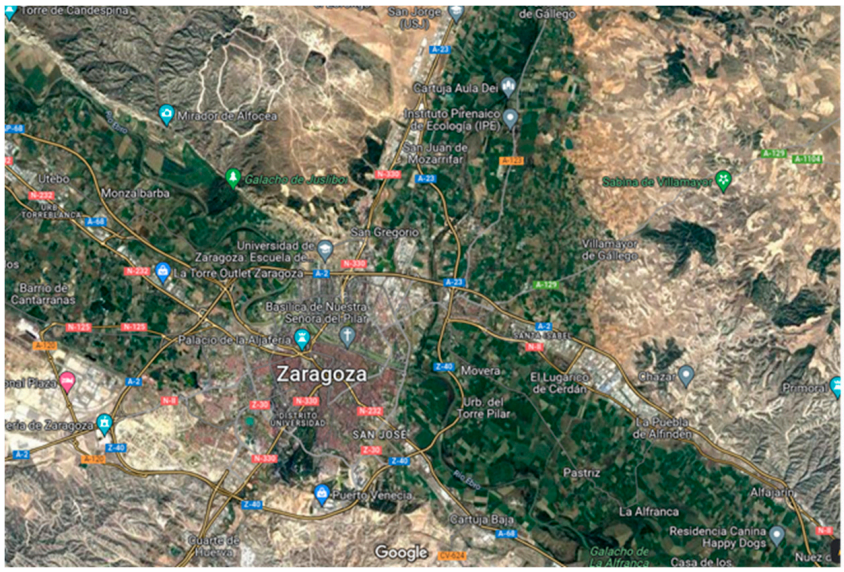
Question 5: In your opinion, how can existing green spaces be improved? Assign an order of importance to each of the following options, with 1st being the most important. If you consider it appropriate, you can assign the same order of importance to more than one option, as well as add new options.

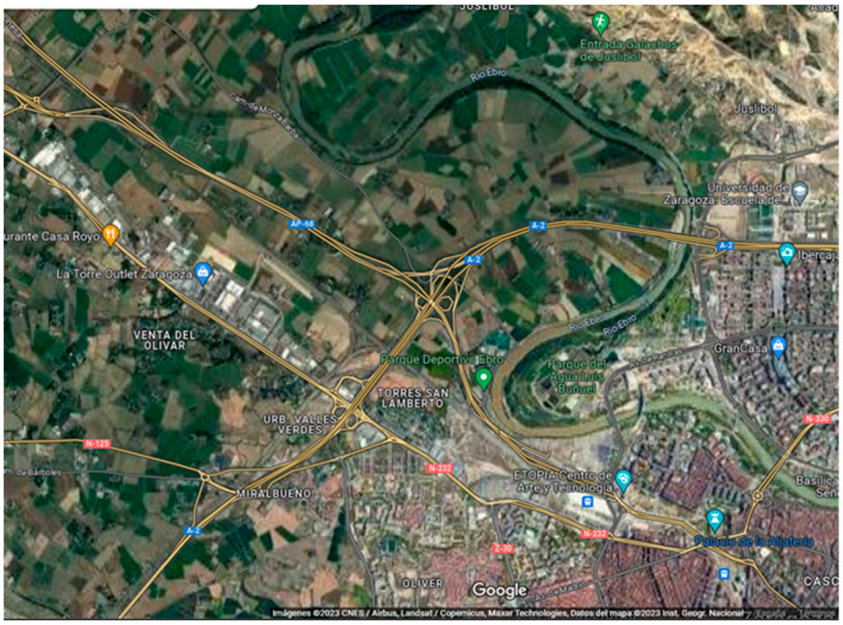
Expanding their size
Improving their naturalness and functioning
Increasing connectivity with other green spaces
Adding recreational and entertainment elements
Facilitating access to green spaces
Increasing investment in maintenance
Other:
Other:

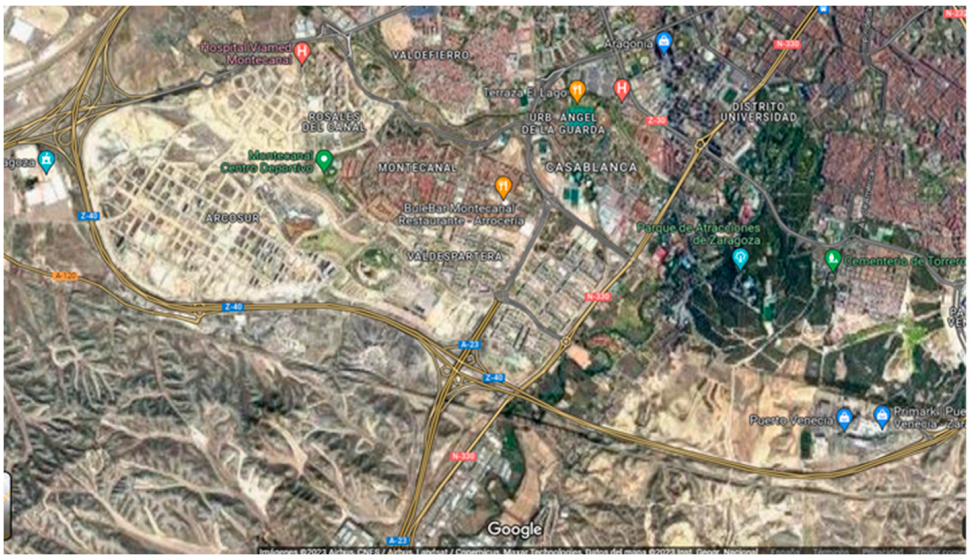
Question 6: Where would you establish new green spaces in different areas of Zaragoza? Assign a preference order to each of the following options, with number 1 being the most important. If you consider it appropriate, you can assign the same preference order to more than one option, as well as add other options.

In the consolidated urban area: from the old town to the third belt (Z-30)
In the non-consolidated urban area: areas between the third (Z-30) and fourth (Z-40) belt, where buildings are being constructed or planned
In the peri-urban area: areas beyond the fourth belt (Z-40) and also some non-built areas or orchards between Z-30 and Z-40.
In the consolidated urban area: from the old town to the third belt (Z-30)
Other:
Other:

Question 7: Mark on these maps some locations where you suggest new green areas could be created to improve Zaragoza's green infrastructure and adapt to climate change. (You can move the star with the cursor to the right of each map to the suggested position and copy it to as many locations as you believe are appropriate to establish new green areas)



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Montecanal Centro Deportivo
MONTECANAL
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ARCOSUR
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VALDESPARTERA
Parque de Atracciones de Zaragoza
Puerto Venecia
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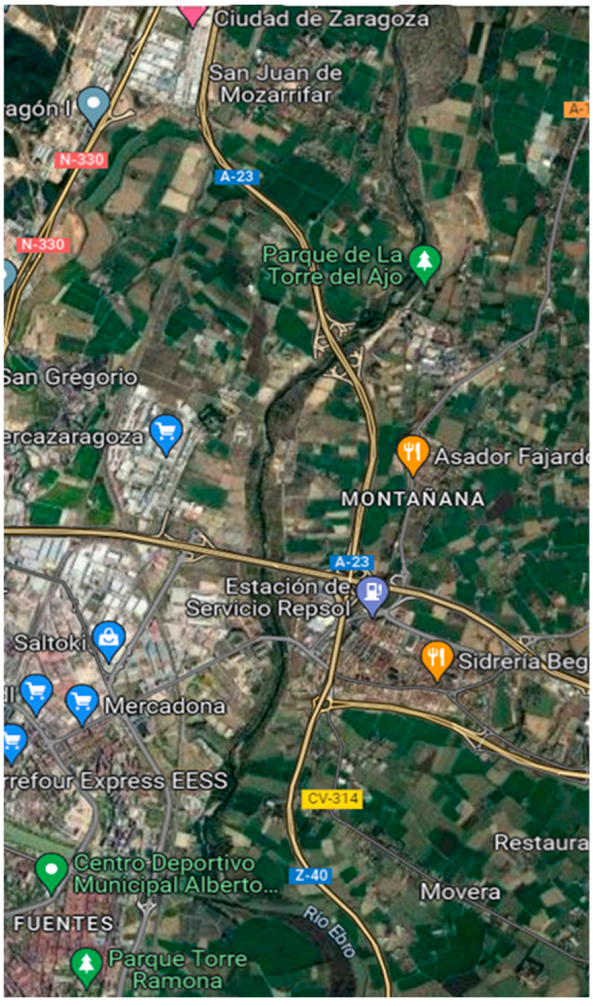
Ciudad de Zaragoza
San Juan de Mozarrifar
N-330
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Parque de La Torre del Ajo
MONTAÑANA
Estación de Servicio Repsol
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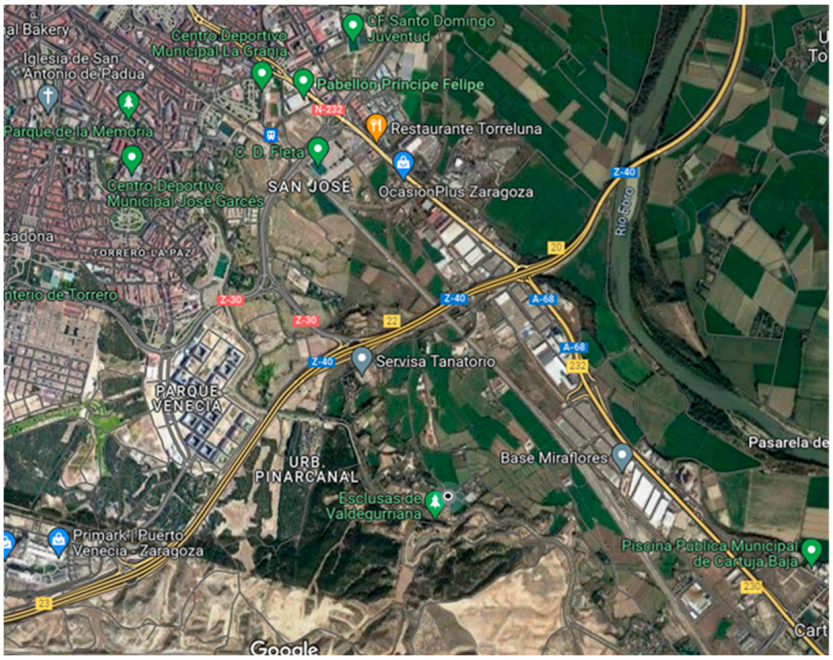
CV-314
Centro Deportivo Municipal Alberto...
Z-40
Movera
FUENTES
Río Ebro
Parque Torre Ramona



Thank you very much for your participation! Please send this completed document to co-min@ipe.csic.es.

If you have any comments or suggestions about the survey or about Zaragoza's green infrastructure, feel free to write them here or contact us directly via email.

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3. GENERAL DISCUSSION

3.1 Updates and Advancements: 2020-2024 in Review

In our first article, we have performed a bibliometric review between the years 1992 and 2020, about urban green infrastructure (UGI) and sustainable development (SD) using the Web of Science (WoS) and the software VOSviewer. We got 195 articles (after filtering and removing the unwanted or irrelevant articles). A lot of updates and advancements might have occurred since 2020. To check if this is true, we performed again on the 7th of March 2024, the same bibliometric review using the WoS, but this time from the year 2020 and 2024. Surprisingly, after the process of filtering the articles and taking out the unwanted ones, we got 506 articles, showing a significant interest increase around the world.

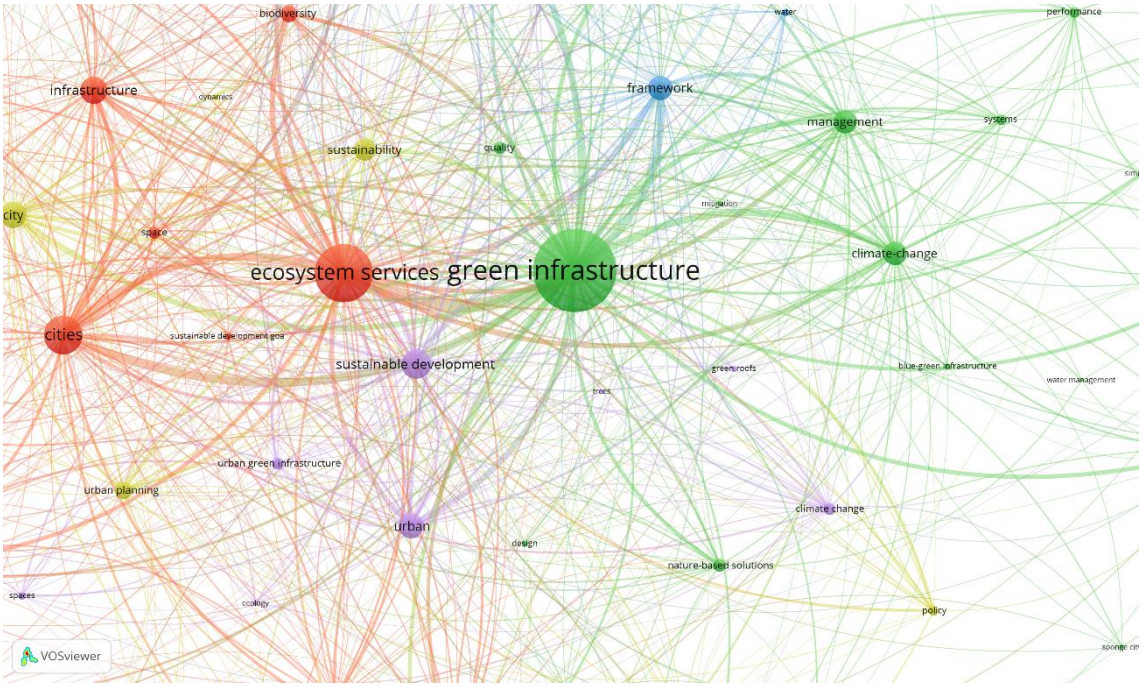

Fig. 5. Keywords most frequently used in the articles reviewed between 2020-2024. Bigger circles correspond to the most used keywords.

The keywords analysis didn't show significant changes in comparison with the keywords analysis graph in the first article of our PhD. "Green infrastructure", "ecosystem services", "sustainable development", "cities" and "climate change" were the most used keywords by the authors to represent the subjects of interest of their papers. Despite the observed increase in interest over the last four years, there remains a significant opportunity to delve into more topics regarding UGI and SD. Consequently, there is opportunities to investigate a wider range of topics associated with UGI and SD, highlighting additional connections within the topic network [90].

Table 3: Citation report of the 10 most cited articles between the 505 articles reviewed.

Title	Authors	Year	Total Citations
Environmental justice in the context of urban green space availability, accessibility, and attractiveness in postsocialist cities	Kronenberg, Jakub; Haase, Annegret; Laszkiewicz, Edyta; Antal, Attila; Baravikova, Aliaksandra; Biernacka, Magdalena; Dushkova, Diana; Filcak, Richard; Haase, Dagmar; Ignatieva, Maria; Khmara, Yaryna; Nita, Mihai Razvan; Onose, Diana Andreea	2020	198
Exploring trade-offs among the multiple benefits of green-blue-grey infrastructure for urban flood mitigation	Alves, Alida; Vojinovic, Zoran; Kapelan, Zoran; Sanchez, Arlex; Gersonius, Berry	2020	186
Towards the progress of ecological restoration and economic development in China's Loess Plateau and strategy for more sustainable development	Li Yurui; Zhang Xuanchang; Cao Zhi; Liu Zhengjia; Lu Zhi; Liu Yansui	2021	166
Using a system thinking approach to assess the contribution of nature based solutions to sustainable development goals	Martin, Eulalia Gomez; Giordano, Raffaele; Pagano, Alessandro; Keur, Peter van der; Costa, Maria Manez	2020	150
Justice in nature-based solutions: Research and pathways	Cousins, Joshua J.	2021	133
What influences the effectiveness of green logistics policies? A grounded theory analysis	Zhang, Wei; Zhang, Mingyang; Zhang, Wenyao; Zhou, Qian; Zhang, Xinxin	2020	124
Not Simply Green: Nature-Based Solutions as a Concept and Practical Approach for Sustainability Studies and Planning Agendas in Cities	Dushkova, Diana; Haase, Dagmar	2020	121
Sustainable urban planning strategies for mitigating climate change in Saudi Arabia	Abubakar, Ismaila Rimi; Dano, Umar Lawal	2020	120
Comprehensive evaluation of urban resilience based on the perspective of landscape pattern: A case study of Shenyang city	Feng, Xinghua; Xiu, Chunliang; Bai, Limin; Zhong, Yexi; Wei, Ye	2020	111

Construction of an ecological security pattern based on ecosystem sensitivity and the importance of ecological services: A case study of the Guanzhong Plain urban agglomeration, China	Chen, Jiao; Wang, Shusheng; Zou, Yitong	2022	86

Although, logically, papers published in 2024 had less time and opportunities to be cited, a noticeable trend from the most cited articles is the diverse approaches employed to address environmental challenges (Table 3). The most cited paper Kronenberg et al., (2020) [91], emphasized the importance of environmental justice in urban green spaces, particularly in postsocialist cities, showing a growing awareness of the need for equitable access to nature in urban areas worldwide. The second paper, by Alves et al. (2020) [92], examined the trade-offs associated with green-blue-grey infrastructure for urban flood mitigation, highlighting the complexity of urban resilience strategies in the face of climate change. Finally, the third most cited paper, by Li et al. (2021) [93], focused on ecological restoration and economic development in China's Loess Plateau, calling for forming an actor-network consists of multi stakeholders, including the central government, local government, watershed, families, ecosystem and environment, enterprises, NGOs, and scientists, and paying attention to ecosystem management, ecological restoration, industrial structure optimization, ecological agriculture, rural infrastructure, and ecological civilization construction in the future development. These papers demonstrated, that there is a clear growing awareness among policy-makers and urban planners about the importance of incorporating sustainable development goals into the urban green infrastructure planning.

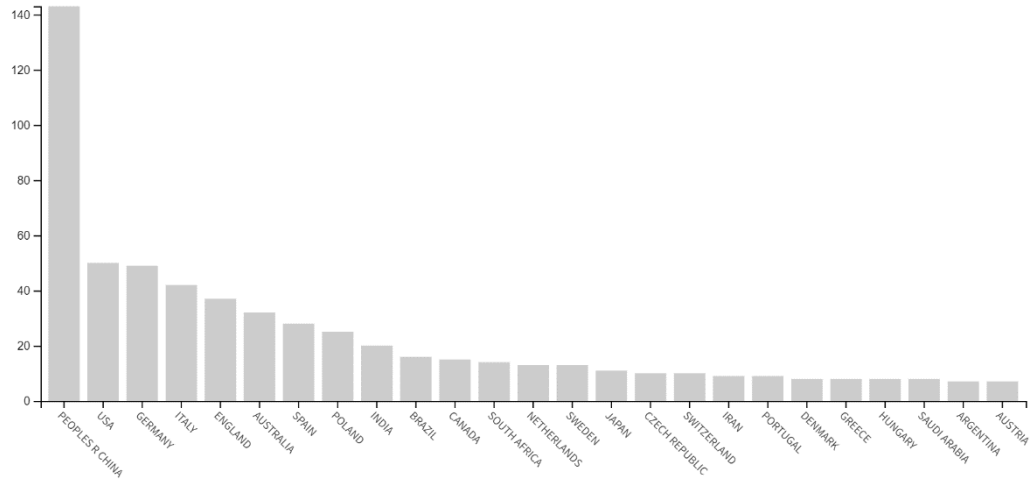

Fig. 6. Number of publications per country. Source: Web of Science (adjusted)

China is the leading country publishing the most articles about UGI and SD, followed by USA. Spain occupied the 7th place. China's position as the leading country could be attributed to unprecedented rapid urbanization and population growth in Chinese cities [94], which have pushed the government to implement policies that focus on sustainable development practices to address environmental concerns such as pollution [95]. Also China

has been investing heavily in research and development across various sectors [96], including environmental sciences and sustainability (Figure 6).

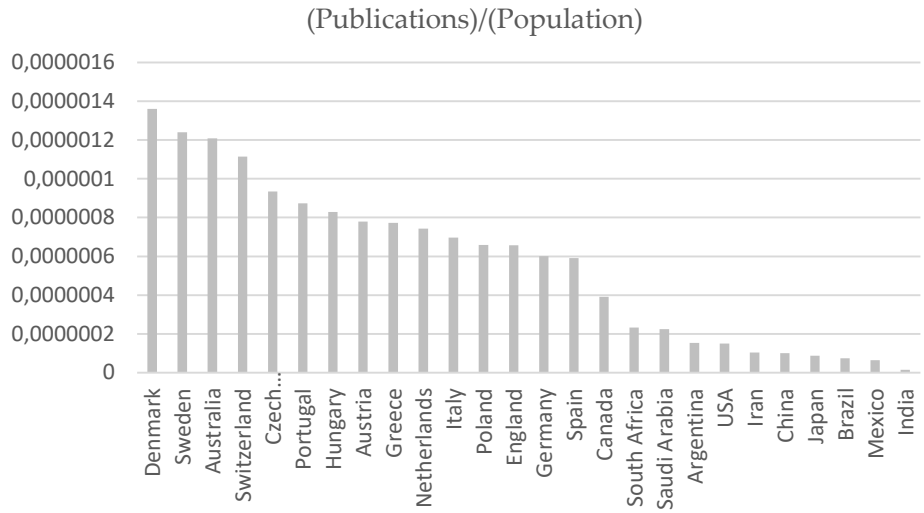

Fig. 7. Publications per population comparison

However, relative to their respective number of publications per population, the order changes (Figure 7).

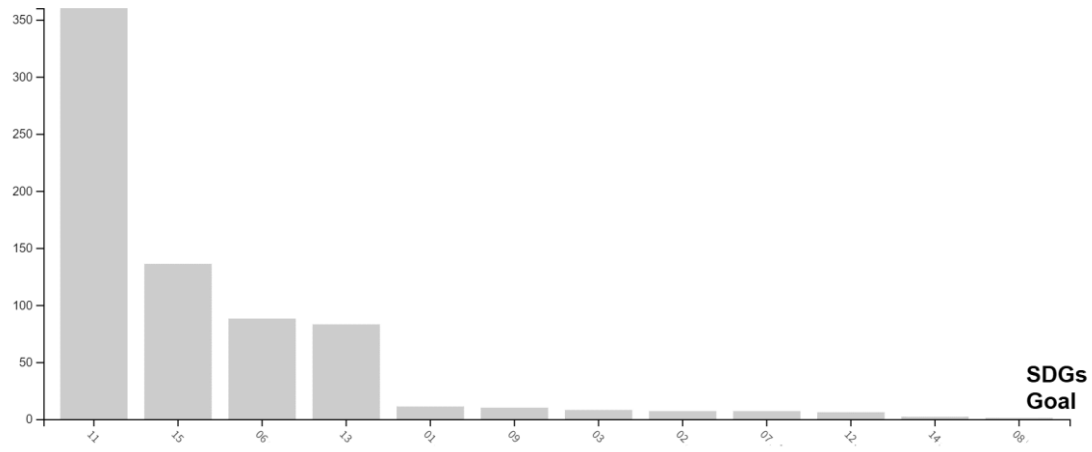

Fig. 8. Correspondences between the documents obtained in this review and SDGs. It is important to note that some article may correspond to more than one SDGs goal. Source: Web of Science (adjusted)

The literature review between 2020 and 2024, showed that the focus now is the same as before 2020: in the first place, on Sustainable Development Goals (SDGs) number 11 (Make cities and human settlements inclusive, safe, resilient and sustainable) and 15 (Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss) (Figure 8). It is evident that UGI serves as a support for achieving SDG 11 and 15 objectives, whether through the creation and preservation of green corridors, the establishment of urban forests, or the implementation of green roofs and walls (Check our second, third and fourth paper). Such

interventions not only mitigate the negative impacts of urbanization but also contribute to the fulfillment of broader sustainable development objectives, providing economic prosperity, social equity, and environmental sustainability [97].

SDG 13 (Take urgent action to combat climate change and its impacts) ranked in fourth place compared to SDGs 11 and 15. UGI elements, such as parks, steppe and urban forests, offer multiple benefits in mitigating the effects of climate change within urban areas by providing benefits including carbon sequestration and heat island mitigation (Check our fourth article). Hence, by prioritizing of UGI projects, cities can become more sustainable, resilient, and capable of addressing the challenges posed by a changing climate [98]. We argue that SDG 13 should be of primary importance, and that the role of achieving urban sustainability should urgently focus on enhancing the capacity of cities to adapt in the face of a rapidly changing climate [99]. As all the SDGs are, more or less, intertwined, we advocate for a more integrative approach during the study of urban green infrastructure. So, the study of UGI should reflect its contributions to all SDGs.

3.2 Conceptual and Methodological Contributions

Research indicated that planners and policy makers may be confused about what constitutes green infrastructure. This may contribute to inaction on climate change adaptation because it muddies existing green-space programs and initiatives [100]. Our dissertation linked the concepts of UGI, sustainable development, ES, and climate change, helping urban planners and policymakers of medium-size cities, particularly in Zaragoza, to strategically plan for enhancing ecosystem services provision. This focus particularly targeted combating climate change.

Therefore, this dissertation has six key contributions:

(1) This dissertation highlighted the relation between UGI and sustainable development, and specifically, the research gap concerning UGI and the United Nations Sustainable Development Goals (SDGs). It conducted a literature review that focused on showing the methodological aspects of UGI research after analyzing the relationships between topics and authors of the reviewed documents. Additionally, it observed the distribution of the topics of interest of the documents concerning the three major pillars of sustainability (environmental, social, and economic). This study represented one of the first attempt to link UGI and SDGs.

(2) This study developed an ecological index for the evaluation of UGI, it was called the Nat & Fun index (Naturalness and functioning index), partly inspired by Machado (2004) [37]. While previous studies used complicated, time consuming, and expensive procedures to evaluate and assess UGI [101], the advantage of the Nat & Fun index lies in its simplicity, and in its cost-effectiveness, as it can be applied without sophisticated methods. Nat & Fun index can be a tool to predict the ES delivery potential of UGI elements. No expensive equipment was required and, at the same time, the index provided an acceptable accuracy.

(3) According to the ES quantification results, this study identified the UGI elements in the city of Zaragoza with the highest ES provisioning, and their values, such as water supply, carbon sequestration, water regulation, soil formation and others (check the third article). Additionally, it studied the trade-off and synergies between the different ES assessed in the UGI in Zaragoza. This research followed the principle that assessing potential differences of ES provision between various types of UGI is crucial to effectively guide appropriate green

infrastructure design and integrate green infrastructure into urban development strategies [102]. This study found out that the ES supplied by UGI in Zaragoza depended on their naturalness, functionality and imperviousness, which is helpful to guide city-planners in planning UGI effectively and efficiently.

(4) Research has shown that landscape designs can have negative impacts on the environment. Unsustainable land development and management practices significantly disturb the elements of ecosystems damaging the soil and vegetation and start a chain of negative effects resulting in reduced infiltration, increase in runoff, excess sedimentation, water pollution, increase in greenhouse gases and energy consumption [103]. This dissertation contributed to constructing a bridge between landscape design and environmental sciences, as it encouraged the professionals working in landscape architecture, planning, and engineering, to prioritize different aspects of sustainability as do researchers and academics [104]. Also based on scientific evidence published in scientific articles, in the later section (Implications for planning and decision-making), this research recommends, sustainable design and planning practices to enhance urban sustainability and the fight against climate change.

(5) In order to develop a plan for the improvement of the UGI to counteract the impacts of climate change, this study proposed a prioritization plan for the preservation and restoration of UGI elements in Zaragoza, not only in the urban populated areas, but also in the peri-urban areas. The researched studied two key ES to buffer climate change impacts; temperature regulation and carbon sequestration, and determined the zones where high values of services are present, which increases their significance and importance. This study is considered a contribution to achieving the desire of the Municipality of Zaragoza to become a neutral city.

(6) This study used a methodology that embraced various analytical approaches to evaluate UGI in Zaragoza. This investigation integrated qualitative methods (in first and second article), quantitative assessment (in second, third and fourth article), spatial data analysis (in second and fourth articles), and expert survey techniques (in the fourth article). This approach aimed to provide a holistic understanding of UGI within the city. By combining these diverse methods, we were able to capture different aspects of UGI, including its qualitative characteristics, quantitative metrics, spatial distribution, and expert perspectives. This is essential to guide policy-making and urban planning decisions aimed at enhancing sustainability and resilience in cities like Zaragoza.

3.3 Research Limitations

As any other research study, the present research study presents a list of limitations, which could be resumed as following:

- Sustainable development is not only dependent on UGI but there are other aspects that are important because sustainable development is also related to human and environmental health, social issues and governance. Energy consumption and mobility are particularly relevant [105]. Therefore, our review of UGI and sustainable development (SD) may be limited in scope as there may be works focusing on sustainable development from different points of view (e.g., energy, mobility, engineering, transportation, hydraulics).

- UGI is not only an investment, but it can help to stimulate the economy as it will improve overall health and safety for humans in addition to various wildlife [106]. An economic efficiency study assessing the economic value of UGI of Zaragoza would have been a plus for deeper understanding, and for figuring out the public and private cost savings of using green infrastructure rather than on gray infrastructure [107].

- This study employed a multifaceted approach, drawing upon a combination of infield observation, ecosystem services assessment and quantification, stakeholder interviews and spatial analysis. However, remote sensing techniques to evaluate UGI were not employed in this dissertation. Future research is recommended using image classification in remote sensing to evaluate the UGI of Zaragoza as these techniques have been shown very useful to study UGI [108]. This could be also useful to understand the benefits of connecting physically UGI sites and to plan their connectivity while the city enlarges but also for consolidated zones.

- This study assessed eight ES of different UGI elements. Six out of eight are regulating ES. It did not encompass more provisioning (e.g., food production) and supporting ES (e.g., pollination), and did not introduce cultural ones (e.g., recreational and educational benefits). It will be interesting to include cultural ES in future studies about ES quantification of UGI in Zaragoza. This would enrich our understanding, expanding the dataset, and offering a broader perspective on the provisioning of ES by the UGI of Zaragoza.

- To combat climate change, this research provided a prioritization plan for the restoration and preservation of UGI, based primarily on the ES of temperature, preferentially in the densely populated zones of the city as it can contribute more to the citizen´s welfare, and carbon sequestration, with preferences for peri-urban zones where restoring larger areas can more to carbon sequestration. However, more studies are necessary for a detailed quantification of the potential of different types of UGI to provide temperature regulation and carbon sequestration. And, specially, a detailed monitoring and evaluation of these two ecosystem services provision by selected UGI elements.

3.4 Implications for planning and decision-making

This research detected a clear pattern in UGI distribution in Zaragoza, to be considered in urban planning. There is a clear separation between natural sites located in suburban and peri urban zones characterized, and most artificial UGIs located in the most densely urbanized parts of the city [109]. Accordingly, it is advisable to keep natural remnants, which are still driven by ecological processes as UGI sites while a city enlarges, and to consider newly-built UGI as a useful tool to restore degraded zones and recover natural dynamics linked to hydro-geomorphological processes. Additionally, it was found that urban parks were the most common UGI type found in Zaragoza showing lack of variety of UGI elements. This study urges urban planner and decisions makers to increase the diversity of the UGI elements. For instance, there is a lack of the presence of green walls and green roofs in Zaragoza, even though, they can provide important environmental, social and economic benefits [110].

Design wise, it is recommended to maintain the structure and relief of UGI sites within urban areas, and if newly designed, to imitate natural features i.e. constructing UGI elements not only with high naturalness but also with high functioning, as keeping ecological functioning is the essential factor to provide ecosystem services and also to save expenditures for UGI maintenance. Regarding plantations, it is suggested to plant indigenous vegetation in accordance with its biogeographic and habitat features, and arrange trees and plants in irregular groupings strategically placed to promote ecological connectivity, rather than having them scattered and isolated without spatial connection. To foster connectivity within the site, native trees and plants of varying heights can be planted gradually. Since urban parks is the most found UGI element in Zaragoza, and due to its environmental and social benefits [111], urban park design should adopt an irregular approach, drawing inspiration from English-style gardens and parks [112], thus avoiding overly regular distributions of natural elements. Similarly, this research recommended the use of irregular shapes in the design of all UGI elements, also asymmetrical distribution of vegetation should be implemented, and flatness should be reduced. The design should start with vegetation, diverse strata, as the primary component and then specifying the artificial components in a way that do not disrupt the internal connectivity of plantations.

To increase ES provisioning, it is recommended as this study has proven, to increase the vegetated area in UGI sites i.e. increasing naturalness. Also to preserve valuable natural remnants and restoring natural urban degraded areas and recovering the natural dynamics i.e. increasing functioning. This includes preservation or promotion of natural soil as the basis for plant growth and vegetation development Furthermore, it recommended to reduce the impermeable surfaces such as roads, and pavements because of their negative consequences on soil quality and ES delivery such as water regulation and water supply. However, if an artificial area is needed to provide cultural ES, then it would be advisable to use sustainable permeable pavement interspersed with natural vegetated areas.

To fight against climate change, Zaragoza should focus its efforts on preserving and restoring peri-urban areas such as steppes, pastures and forests, taking into account the soil characteristics. It was demonstrated that these sites have remarkable potential to stock carbon into the soil. Therefore, the restoration efforts should not only be focused at the city scale but also at a larger scale in order to address the challenges of environmental conservation and climate resilience.

Adapting the viewpoint could prove cost-effectiveness over time and unveil hidden information and mechanisms that urban planners may have neglected. When it comes to regulating temperature inside the city, urban parks and rivers should be the top targets for restoration efforts. Therefore, urban planners and decision-makers should concentrate on restoring, the riverbanks and parks by adding vegetation in diverse strata and creating comfortable shelters. These areas have a high potential to be climate refuges, especially in the hot summer weather of Zaragoza.

We believe that cities and urban zones cannot achieve sustainable development by themselves. This statement is based on the fact that cities, for example Zaragoza, obtain their raw materials (energy, water, construction materials, and food) to grow and maintain from outside the urban zone, from rural or non-built areas. Therefore, a budget of the city's activities to quantify expenditures and contributions to sustainability (e.g., carbon budget) should

include the import and export of raw materials. This concept could be extended to the past, as the imported materials in the past contributed to the present budget of any characteristics used to estimate the balance. As a result, we encourage an alliance of urban and rural zones to contribute to sustainable development [1].

Currently, UGI designers and planners have demonstrated limited ability to integrate ecological principles into their work. Urban planners have often marginalized environmental health and ecological processes, resulting in negative effects on human well-being [113]. Therefore, in order to create natural and functional UGI, there needs to be a change in the perspective of decision makers and urban planners. There should be more emphasis on ecological understanding, restoration ecology and environmental management in their design approach. Also, to run the way towards a neutral city. It is recommended that increased coordination between the departments of urbanism and green infrastructure be prioritized. By stronger collaboration and sharing resources between different departments, the municipality can ensure more coherent and sustainable urban development that will aid to achieve its goal of combating climate change. As said above, sustainability will require alliance with rural areas.

4. CONCLUSIONS

The main conclusions of this Doctoral Thesis are:

1. The number of scientific studies on UGI in relation to sustainable development has increased exponentially during the last decade and, particularly, during the last four years. There is a high variety of quantitative topics researching UGI and sustainable development, but few papers including the three pillars of sustainability in their methods, with the majority focuses on environmental topics. Therefore, a lack of integrative and holistic studies were observed.

2. Recently, literature is emphasizing on SDGs11 and 15, aimed at creating resilient, and sustainable cities and preserving terrestrial ecosystems. UGI emerges as an important tool in advancing these objectives. While SDG 13, addressing directly climate change, ranked fourth in priority, UGI elements such as parks and urban forests provide significant climate change mitigation benefits like carbon sequestration and heat island mitigation. Therefore, urgent attention to SDG 13 is recommended, asserting that enhancing cities' adaptability to climate change should be a primary focus to achieve urban sustainability.

3. Naturalness (Nat) indicates the degree of natural versus artificial components forming the UGI site. A grading system ranking from completely natural (10) to completely artificial (0) sites was established. An analogous scale was established to assign values for functioning (Fun), which was defined as the degree of natural processes driving the dynamics of the UGI site based on the classical concept of ecosystem functioning. The values of Fun ranged from 0 to 10, with 0 indicating non-functional sites highly influenced by humans, and 10 pointing to complete preservation of natural of hydro-geomorphological features and processes.

4. Most Zaragoza UGIs are characterized by low Nat and Fun, especially those located in the intensively urbanized zones. They include a wide range of UGIs elements such as urban parks, university parks and squares. Another group of UGI sites showed slightly higher values of Nat but low values of Fun. These sites mostly represented certain urban parks and street trees (road alignment) with regular plantations of trees that maintain some natural components combined with above- ground artificial facilities for recreation and public recreation. Few sites showed a high Nat but a low Fun value which corresponded to an urban agricultural land and two roundabouts. However, those located in periurban zones are characterized by the preservation of their hydro geomorphological features. Therefore, they have high Nat & Fun and dominated by natural sites that included rivers, riparian areas, forests, meanders, and a large urban forest. The combination high Fun and low Nat does not proceed ecologically, it is not represented in our Nat & Fun space by any UGIs.

5. Nat and Fun showed a positive relationship with the size of the UGI site, the vegetation cover, vegetation strata and natural subsoil area. Both Nat and Fun are and inversely related with the degree of regularity forms and flatness in the design of UGIs, artificial soil cover. Nat and Fun are, logically highly related. Rivers and urban forests have

larger area, richer vegetation, less disturbed soils, less flat soil, a higher degree of naturalness, and better functionality compared to urban parks situated in flat terrains with artificial soil and vegetation. There should be a broader array of UGI Nat & Fun combinations if the developing city want to preserve ecological features and processes in UGI sites.

6. The UGI sites of Zaragoza provided low ecosystem services because of the lack of naturally vegetated zones (naturalness) maintained with hydro- geomorphological processes (functioning) in contrast with the dominance of impervious surfaces and artificial elements in most UGI sites. Natural UGI elements such as river, meanders, urban forest, steppe, natural forest provided the highest temperature regulation, water supply, carbon sequestration, and water regulation. On the other hand, UGI sites such as urban and university parks, roundabout, canal, agricultural land provided the highest value of humidity regulation, nutrient regulation while waste regulation and soil formation were the lowest ecosystem services delivery across all UGI sites.

7. Underlying mechanisms govern the supply of ecosystem services in UGI. There is strong interrelationships between different ecosystem services in the UGI of Zaragoza. The study showed that water supply, soil formation, carbon sequestration, and temperature regulation are all significantly and positively correlated with water regulation. This suggests that water regulation is a key ecosystem service that can act as surrogate of several other ecosystem service. Similarly, waste regulation was found to be significantly correlated with soil formation and carbon sequestration.

8. The peri-urban zones can play a crucial role in mitigating climate change by acting as valuable carbon sinks. UGIs in peri-urban areas are big areas that tend to show higher capacities for carbon sequestration compared to their city counterparts. Comparing the city scale and municipality scale has shown that the green infrastructure in peri-urban zones has an important role in the provision of ecosystem service. Additionally, they offer a diversity of urban green infrastructure elements that are not present in the city, such as pastures, where soils under a range of pasture types have considerable potential for sequestration of atmospheric CO_2.

9. To mitigate the impacts of climate change in the city, the highest restoration priority should go to riparian areas of the rivers and parks because they have a high potential to regulate temperature and to be climate refuges, especially in the hot summer weather of Zaragoza. As for peri-urban areas, priority analysis also showed that the highest restoration priority should go to high-functioning green infrastructure sites such as pastures, then to forests and steppes due to their large area and their capacity for carbon intake.

CONCLUSIONES

Las principales conclusiones de esta Tesis Doctoral son:

1. El número de estudios científicos sobre la UGI en relación con el desarrollo sostenible ha aumentado exponencialmente durante la última década y, particularmente, durante los últimos cuatro años. Existe una gran variedad de temas cuantitativos que investigan la UGI y el desarrollo sostenible, pero pocos artículos incluyen los tres pilares de la sostenibilidad en sus métodos, y la mayoría se centra en temas ambientales. Por lo tanto, se observa una falta de estudios integradores y holísticos.

2. Recientemente, la literatura está haciendo hincapié en los ODS 11 y 15, destinados a crear ciudades resilientes y sostenibles y preservar los ecosistemas terrestres. La UGI surge como una herramienta importante para promover estos objetivos. Si bien el ODS 13, que aborda directamente el cambio climático, ocupó el cuarto lugar en prioridad, los elementos de la UGI, como los parques y los bosques urbanos, brindan importantes beneficios de mitigación del cambio climático, como el secuestro de carbono y la mitigación de islas de calor. Por lo tanto, se recomienda prestar atención urgente al ODS 13, afirmando que mejorar la adaptabilidad de las ciudades al cambio climático debe ser un enfoque principal para caminar hacia la sostenibilidad urbana.

3. Naturalidad (Nat) indica el grado de componentes naturales versus artificiales que forman el sitio UGI. Se estableció un sistema de clasificación que va desde sitios completamente naturales (10) hasta sitios completamente artificiales (0). Se estableció una escala análoga para asignar valores de funcionamiento ecológico (Fun), que se definió como el grado de procesos naturales que impulsan la dinámica del sitio de la UGI con base en el concepto clásico de funcionamiento del ecosistema. Los valores de Fun variaron de 0 a 10, donde 0 indica sitios no funcionales altamente influenciados por los humanos y 10 indica la preservación completa de las características y procesos naturales (hidrogeomorfológicos, procesado de materia orgánica) .

4. La mayoría de las UGI de Zaragoza se caracterizan por una baja Nat y Fun, especialmente aquellas ubicadas en las zonas intensamente urbanizadas. Incluyen una amplia gama de elementos UGI como parques urbanos, parques universitarios y plazas. Otro grupo de sitios UGI mostró valores ligeramente más altos de Nat pero valores bajos de Fun. Estos sitios representaban en su mayoría ciertos parques urbanos y árboles en las calles (alineación de carreteras) con plantaciones regulares de árboles que mantienen algunos componentes naturales combinados con instalaciones artificiales sobre el suelo para recreación y recreación pública. Pocos sitios mostraron un valor Nat alto pero un valor Fun bajo, lo que correspondía a un terreno agrícola urbano y dos rotondas. Sin embargo, aquellas ubicadas en zonas periurbanas se caracterizan por la preservación de sus características hidrogeomorfológicas. Por lo tanto, tienen un alto Nat & Fun y están dominados por parajes naturales que incluyen ríos, zonas ribereñas, bosques, meandros, estepas y un gran bosque urbano. La combinación de alta Fun y baja Nat no es ecológica, no está representada en nuestro espacio Nat & Fun por ninguna UGI.

5. Nat y Fun mostraron una relación positiva con el tamaño del sitio UGI, la cubierta vegetal, los estratos de vegetación y el área del subsuelo natural. Tanto Nat como Fun están inversamente relacionados con el grado de regularidad de las formas y planitud en el diseño de las UGI, coberturas artificiales del suelo. Nat y Fun están, lógicamente, muy relacionados. Los ríos y los bosques urbanos tienen una superficie mayor, una vegetación más rica, suelos menos perturbados, suelos menos planos, un mayor grado de naturalidad y una mejor funcionalidad en comparación con los parques urbanos situados en terrenos planos con suelo y vegetación artificiales. Debería haber una gama más amplia de combinaciones Nat & Fun si la ciudad en desarrollo quiere preservar las características y procesos ecológicos en los sitios UGI.

6. Los sitios UGI de Zaragoza proporcionaron bajos servicios ecosistémicos debido a la falta de zonas de vegetación natural (naturalidad) mantenidas con procesos hidrogeomorfológicos (funcionamiento) en contraste con el predominio de superficies impermeables y elementos artificiales en la mayoría de los sitios UGI. Los elementos naturales de la UGI, como ríos, meandros, bosques urbanos, estepas y bosques naturales, proporcionaron la mayor regulación de temperatura, suministro de agua, secuestro de carbono y regulación del agua. Por otro lado, los sitios UGI, como parques urbanos y universitarios, rotondas, canales y tierras agrícolas, proporcionaron el valor más alto de regulación de la humedad y regulación de nutrientes, mientras que la regulación de desechos y la formación del suelo fueron los servicios ecosistémicos más bajos en todos los sitios UGI.

7. Los mecanismos subyacentes gobiernan la oferta de servicios ecosistémicos en la UGI. Existen fuertes interrelaciones entre los diferentes servicios ecosistémicos en la UGI de Zaragoza. El estudio demostró que el suministro de agua, la formación del suelo, el secuestro de carbono y la regulación de la temperatura están correlacionados significativa y positivamente con la regulación del agua. Esto sugiere que la regulación del agua es un servicio ecosistémico clave que puede actuar como sustituto de varios otros servicios ecosistémicos. De manera similar, se encontró que la regulación de desechos estaba significativamente correlacionada con la formación de suelo y el secuestro de carbono.

8. Las zonas periurbanas pueden desempeñar un papel crucial en la mitigación del cambio climático al actuar como valiosos sumideros de carbono. Las UGI en áreas periurbanas son áreas grandes que tienden a mostrar mayores capacidades de secuestro de carbono en comparación con sus contrapartes urbanas. La comparación de la escala de ciudad y la escala de municipio ha demostrado que la infraestructura verde en las zonas periurbanas tiene un papel importante en la prestación de servicios ecosistémicos. Además, ofrecen una diversidad de elementos de infraestructura verde urbana que no están presentes en la ciudad, como los pastos y estepas, donde los suelos tienen un potencial considerable para el secuestro de CO_2 atmosférico y, particularmente en Zaragoza por la presencia de yeso, de biodiversidad.

9. Para mitigar los impactos del cambio climático en la ciudad, la máxima prioridad de restauración debería ir a las zonas ribereñas de los ríos y parques porque tienen un alto

potencial para regular la temperatura y ser refugios climáticos, especialmente en el caluroso verano de Zaragoza. En cuanto a las zonas periurbanas, el análisis de prioridades también mostró que la máxima prioridad de restauración debería concederse a los sitios de infraestructura verde de alto funcionamiento, como los pastos, y luego a los bosques y las estepas debido a su gran superficie y su capacidad de absorción de carbono.

APPENDIX

Impact factor of the journals

Journal	Journal Impact factor	Quartile
Sustainability	3.889 (2021)	Q2
Urban Forestry & Urban Greening	6.4 (2022)	Q1
Urban Ecosystems	2.9 (2022)	Q2
Land	3.9 (2022)	Q2

Thematic areas of the publications included in the Doctoral Thesis:

1. "Urban Green Infrastructure and Sustainable Development: A Review". Sustainability 2021, 13, 11498 https://doi.org/10.3390/su132011498. **Thematic area: Science Edition - GREEN & SUSTAINABLE SCIENCE & TECHNOLOGY; Science Edition - ENVIRONMENTAL STUDIES**

2. "Evaluating naturalness and functioning of urban green infrastructure". Urban For. Urban Green.2023, 80, 127825. https://doi.org/10.1016/j.ufug.2022.127825. **Thematic area: Science Edition - ENVIRONMENTAL STUDIES; Science Edition - URBAN STUDIES**

3. "The ecosystem services supplied by urban green infrastructure depend on their naturalness, functionality and imperviousness". Urban Ecosyst 27, 187–202 (2024). https://doi.org/10.1007/s11252-023-01442-9. **Thematic area: Science Edition - BIODIVERSITY CONSERVATION; Science Edition - ECOLOGY**

4. "Scenario Analysis of Green Infrastructure to Adapt Medium-Size Cities to Climate Change: The Case of Zaragoza, Spain". Land 2024, 13, 280. https://doi.org/10.3390/land13030280. **Thematic area: Science Edition - ENVIRONMENTAL STUDIES**

Justification of the contribution of the PhD student in the works carried out in co-authorship:

1. "Urban Green Infrastructure and Sustainable Development: A Review". Sustainability 2021, 13, 11498 https://doi.org/10.3390/su132011498; **Roles: conceptualization, methodology, formal analysis, writing—original draft preparation, writing—review and editing.**

2. "Evaluating naturalness and functioning of urban green infrastructure". Urban For. Urban Green.2023, 80, 127825. https://doi.org/10.1016/j.ufug.2022.127825; **Roles: investigation, data curation, visualization, writing – original draft, editing, review.**

3. "The ecosystem services supplied by urban green infrastructure depend on their naturalness, functionality and imperviousness". Urban Ecosyst 27, 187–202 (2024). https://doi.org/10.1007/s11252-023-01442-9; **Roles: conceptualization, methodology, formal analysis, investigation, data curation, writing—original draft preparation, writing—review and editing, visualization**

4. "Scenario Analysis of Green Infrastructure to Adapt Medium-Size Cities to Climate Change: The Case of Zaragoza, Spain". Land 2024, 13, 280. https://doi.org/10.3390/land13030280; **Roles: conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, writing—review and editing, visualization.**

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