

Remote Sensing Technologies for Mapping Ecosystem Services: An Analytical Approach for Urban Green Infrastructure

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Abstract: Urban Green Infrastructures (UGIs) have gained increasing relevance in the field of climate adaptive design because of their capacity to provide regulating ecosystem services apt to respond to the impacts of global warming with short-term strategies. The effectiveness of UGIs in reducing climate risks depends on both the state of natural resources and the understanding of urban ecosystem processes over time. The implementation of analytic methods to better understand urban ecosystem dynamics, as well as the local effective potential of ESs, is crucial for addressing climate impacts in cities. The advances in remote sensing methodologies for mapping and monitoring urban ecosystems represent a key opportunity to deepen the ecological features of existing urban green areas as a potential planning asset to respond to climate impacts. Indeed, remote sensing technologies implement a new data-driven planning approach that enables models and simulations of different project scenarios by supporting planning decisions and reducing the risk of failures. According to these assumptions, this paper discusses the results of a literature review aimed at providing the current state of the art in applying remote sensing technologies for mapping and monitoring ecosystem services, focusing on operational opportunities in urban environments. It examines how remote sensing can depict ESs and ensure data quality and reliability for UGI design. The emphasis is on the potential of ESs to mitigate and adapt to heat wave risks which will be more frequent in the next decade, particularly in cities, as highlighted by the IPCC Report 2023. Therefore, UGIs are strategic tools for addressing heat wave impacts, necessitating a shift from empirical approaches to analytical, data-driven planning methods.

Keywords: urban green infrastructure; remote sensing; climate adaptation design; climate risk reduction; ecosystem mapping; heat wave



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1. Introduction

The European Commission defines Green Infrastructure (GI) as a “strategically planned network of natural and semi-natural areas with other environmental features strategically designed and managed to deliver a wide range of ecosystem services (ESs)” [1]. They sustain human life and biodiversity, support material and immaterial cycles, and enhance the values and services of both natural and urbanized systems [2,3].

Initially theorized as “ecological networks” for landscape protection and management [4], GIs are now achieving increasing importance in the field of climate adaptive design thanks to their ability to cope with the impacts of climate change, notably, those connected to climate regulation [5–7]. According to these definitions, Urban Green Infrastructures (UGIs) correspond to a human-generated ecosystem, focused on the request for hybrid performances that respond to biological needs—necessary to guarantee the ecosystem robustness—and anthropic requests for a reduction in climate impacts on urban areas.

The effectiveness of UGIs in responding to climate change depends on the capacity of urban green areas to provide ESs, making UGIs a priority in urban planning and environmental design disciplines [8,9]. Recent studies have highlighted the need to go beyond

empirical approaches to UGI design to ensure that the allocation of economic resources for greening projects and programs produces tangible benefits for the urban environment. Data-driven tools have been developed to quantify and compare the performances of UGIs, using methodologies for mapping and monitoring ESs to guide design and implementation decisions [10]. These tools utilize knowledge as both a cognitive and operational tool to minimize uncertainty and error in decision-making processes [11,12].

Remote sensed data have become a key component in this process [13]. Over the past two decades, advancements in multispectral and hyperspectral optical sensors for Earth Observation (EO) have significantly enhanced the analysis of urban green areas. These sensors capture image data at different wavelengths across the electromagnetic spectrum, enabling detailed examination of various surface characteristics [14]. EO applications allow for the measurement and monitoring of critical parameters, such as the quantity and quality of vegetation, surface and air temperatures, and changes in land cover. These parameters are essential for studying climate impacts in urban areas as they significantly influence the capacity of urban green areas to mitigate the effects of climate change [6,15].

Moreover, integrating remote sensing data with Geographic Information Systems (GISs) enables spatial analysis and design strategy modeling, facilitated by digital tool interoperability [16]. This integration helps identify suitable areas for prioritizing greening strategies through the measurement of specific achievable performances [8].

Despite these advancements, there remains a critical gap in the comprehensive integration of these methodologies into the urban planning and environmental design fields. The existing reviews on mapping GIs or ESs often focus on single-discipline methods and typically address environmental issues at a single spatial scale. This highlights the need for a more holistic approach.

By conducting a comprehensive scoping review, this study addresses this significant gap by identifying remote sensing methodologies that evaluate the comprehensive functionality of GI across multiple scales. Our goal is to provide clear insights into the performance required from a UGI for climate adaptation and mitigation, particularly in response to the phenomenon of heat waves. The focus on heat wave hazards emphasizes the importance of developing UGI design strategies at the urban scale to mitigate and adapt to rising temperatures.

Additionally, we strive to understand how the scientific community adopts remote sensing methodologies for UGI projects and identify which indicators have been standardized by the literature as key references in the design process. The aim is to seek a reasonably reduced panel of indicators that allow for functional mapping of ESs through remote sensing, defining the set of environmental performance metrics that different urban green areas can provide.

Through this approach, we endeavor to contribute to the broader academic discourse on integrating advanced technologies into the climate-adaptive design processes.

Apart from the Introduction, this document consists of four sections. In the Section 1, we outline the main definitions and assumptions utilized in the scoping review process, which help us define the research objectives and the theoretical framework. The Section 2 details our methodology, where we employ a scoping review process with a funnel approach to address our research objectives systematically. The Section 3 presents the results obtained with the funnel approach of the methodology. Finally, the Section 4 discusses these results and proposes future research directions.

This study is part of the Horizon Europe KNOWING project (2022–2026), which aims to develop knowledge, solutions, and tools to help identify decarbonization pathways that combine sustainability and resilience adapted to local contexts.

2. Materials and Methods

2.1. Preliminaries and Assumption

UGIs support climate adaptation by integrating different spatial and functional components of urban green areas across different scales [1,17,18]. Each spatial element of UGI

requires specific datasets and approaches and yields distinct benefits to meet specific needs and purposes [16]. Ecosystem mapping, based on the availability and resolution of satellite data, is a key step in identifying UGI components that should be prioritized to enhance ecosystem services and the overall effectiveness of the network.

An effective UGI ensures that individual elements of the network are designed to adapt to both the existing natural system and the overall anthropized infrastructure system. This provides a robust response to climate impacts, contributing, at the same time, to the effectiveness of the green network. These elements are classified by numerous studies in the field of Landscape Design and Ecology as core areas, hubs, corridors, and stepping stones [2,4,16,19].

The use of remote sensing methodologies for GI planning often focuses on the application of core areas, as these intact habitat zones are essential for supporting focal species and are therefore frequently subject to protection regimes for their ecological importance [16,19] (Figure 1). Core habitats connect hubs and patches through green corridors at a metropolitan or even regional scale, where remote sensing technologies support the analysis of biodiversity, habitat types, land patterns, and transformation dynamics [20]. This approach enables mapping and monitoring the impacts of natural and anthropogenic processes like vegetation fragmentation and the loss of ecological connectivity. Alongside core areas, corridors are also key components for the overall functioning of the network and are mapped through remote sensing for the same purposes. Conversely, stepping stones are smaller habitat patches crucial within urban systems, such as backyards, green roofs, pocket parks, and ponds. For these areas, remote sensing applications require a higher spatial and temporal resolution to map ecosystem services and prioritize green strategies [21].

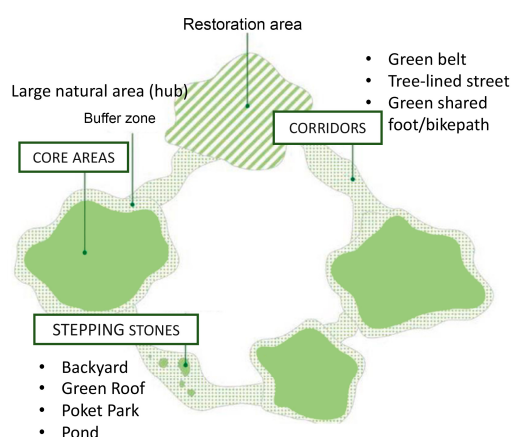


Figure 1. The spatial components of Green Infrastructure.

Although hubs and stepping stones are key elements for implementing UGI as climate adaptation systems, the urban-scale application of remote sensing technologies remains underexplored. To address this, in the final stage of our analysis, we focused our literature review on urban-scale methodologies and indicators, particularly considering the impacts of heat wave hazards and the urban heat island (UHI) phenomenon, which reduce the efficiency of UGIs in terms of ESs (Figure 2).

We emphasize the application of remote sensing in UGI projects with a specific focus on heat wave hazards as they represent a critical emerging urban issue that necessitates intelligent, systemic, and rapid adaptation strategies, as highlighted in numerous climate studies and reports, including those by the IPCC. Heat waves increase energy consumption, elevate greenhouse gas emissions and air pollution, exacerbate the UHI effect, pose threats to natural ecosystems, cause discomfort and health risks for humans, and impact biodiversity. Furthermore, numerous studies highlight the potential of remote sensing methodologies to offer invaluable data on key variables such as surface temperature, land cover, and albedo. These data are crucial for accurately mapping and understanding the

spatial distribution and intensity of heat wave hazards. By integrating remote sensing data, we can better assess and mitigate these impacts at different spatial scales—regional, urban, and district. This allows us to optimize UGI’s role in regulating ecosystem services, including air quality and climate regulation, water flow management, erosion prevention, and biodiversity conservation, as well as providing cultural and recreational benefits. Thus, remote sensing becomes a pivotal tool in enhancing the environmental performance and effectiveness of UGIs.

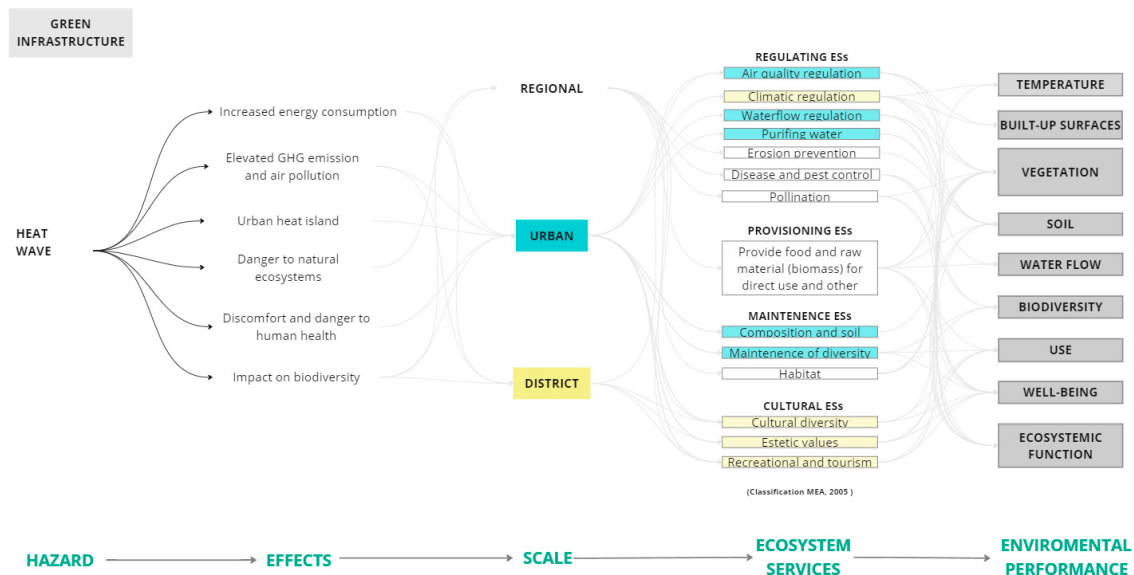


Figure 2. Ecosystem services framework for heat waves in the multiscale approach.

2.2. Steps in Method

This literature review employs a scoping review methodology, guided by the framework established by Arksey and O'Malley [22], to address the research objectives concerning UGI and remote sensing technologies systematically. Using this approach, we adopt a funnel methodology to consider various aspects of UGI planning and design in both spatial and functional terms.

According to Arksey and O'Malley's framework, the methodological approach for this scoping review is structured into four distinct stages as follows:

1. Identification of research objectives for search string construction.
2. Identification of relevant studies to define inclusion/exclusion criteria.
3. Data monitoring and sorting of information according to key questions and assumptions.
4. Collection, synthesis, and reporting of results according to the research objectives.

To support this comprehensive analysis, we selected the Scopus search engine because of its extensive and reliable database, which encompasses a wide range of peer-reviewed literature across various disciplines. Scopus offers robust search functionalities and comprehensive coverage, ensuring the inclusion of high-quality sources. After conducting the initial search, we utilized VOSviewer to perform a detailed bibliometric analysis. This analysis provided insights into keyword occurrences and helped identify relevant authors, with a threshold set for keyword occurrences greater than five. The use of VOSviewer enabled the visualization of bibliometric networks, elucidating key relationships within the research field.

2.3. Step 1: Identification of Research Objectives for Search String Construction

In the first step of the method, the research objectives were identified considering three main aspects of remote sensing applications for UGI plans and projects. This involved a methodological framework consisting of a three-phase scoping process, following a funnel

approach that begins with a broad overview and narrows down to specific objectives. The following process was instrumental in constructing the search strings (Figure 3):

- The first phase covered the general concept and application of remote sensing methodologies for GI planning, reflecting large-scale projects at metropolitan or regional levels. In terms of approach, this phase considered various hazards, including heat waves, but is not limited to them.
- In the second phase, the keywords of search strings were more closely aligned with the concept of remote sensing for GI design at the urban scale. This phase emphasized the key role of interoperable analytical tools for ecosystem service modeling and scenario-based simulations.
- In the final phase, we applied an additional filter to focus our results specifically on heat wave studies. This targeted approach aimed to refine the scope of the investigation and analyze and compare remote sensing methodologies for climate adaptation of GI in urban areas.

Based on this methodological framework, the research objectives were established as follows:

- (1) Examine the breadth, scope, and nature of research activities in the application of remote sensing technologies for GI planning.
- (2) Provide a clear overview of data-driven methodologies and ecosystem-based approaches that employ urban-scale satellite data for UGI design.
- (3) Describe a research framework for the climate-adaptive design of UGI aimed at mitigating heat waves through a data-driven process using remote sensing technologies.

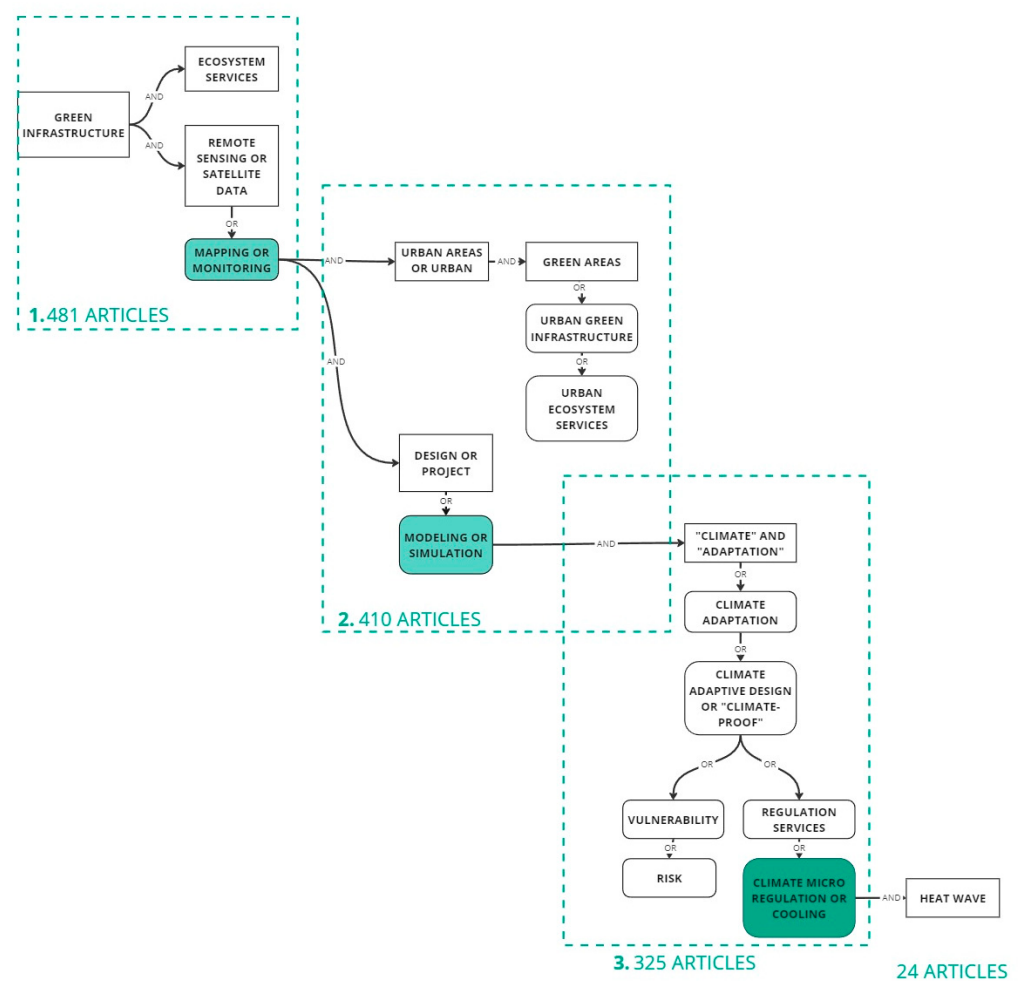


Figure 3. The three phases of the methodological scoping process.

2.4. Step 2: Identification of Relevant Studies and Inclusion/Exclusion Criteria

In the second step of the method, relevant studies were identified to structure the literature analysis process. This step allowed us to determine the reference period for this study and define the inclusion and exclusion criteria (Table 1). Given the extensive consolidation of the GI topic in the scientific literature and international policy documents, it was crucial to establish a solid scientific basis to connect with remote sensing methodologies.

Table 1. Inclusion and exclusion criteria.

Criteria	Description
Disciplinary criteria	Excluded specific thematic areas to focus this study more effectively.
Temporal criteria	Focused on studies from 2005 onwards to align with the consolidation of the ecosystem service concept.
Conceptual criteria	Utilized progressively refined keywords and search strings to identify studies relevant to the research objectives.
Relational criteria	Ensured accurate selection based on preliminary analysis hierarchies.

A preliminary analysis compared the notion of “Green Infrastructure” with “Urban Green Infrastructure,” revealing that the former is more widely discussed in the scientific literature across various disciplines and geographical areas. Consequently, “Green Infrastructure” was adopted as the main search term, with the requirement that this term must appear in the title of the selected studies to ensure relevance to our research objectives.

The scientific interest in UGI has undergone a significant evolution in the consolidation of the concept of ecosystem services, favored by the solid scientific basis laid by the Millennium Ecosystem Assessment [5] and the emerging theories of Urban Ecology [22,23]. After identifying relevant studies [1,2,4,6,24,25], we paid particular attention to the development of the inclusion and exclusion criteria.

2.5. Step 3: Data Monitoring and Sorting of Information According to Key Questions and Assumptions

In the third step of the method, data tracking and information organization followed the three-phase scoping process framework we utilized to set the research objectives (Section 2.3). This systematic approach ensured that search strings, initially formulated based on previous studies and existing knowledge, were progressively refined to focus on and address each research objective in each phase (Figure 3).

Initially, search strings were formulated based on insights from previous studies on Green Infrastructure, ecosystem services, and remote sensing techniques for mapping and monitoring urban ecosystems. These search strings were iteratively refined by selecting relevant keywords based on their occurrence in search results, which helped to define a precise research framework aligned with the objectives.

Next, data structuring involved refining terms related to GI in urban areas and their relationship with the environmental design field. Recurring keywords at the urban project scale, as well as those related to data-driven methodologies such as modeling and simulation, were integrated to provide a comprehensive view of remote sensing applications in UGI studies.

Finally, the state of knowledge on remote sensing technologies for UGI was evaluated, particularly in the context of adaptive climate design for heat wave hazards. Keywords most relevant to describing strategies for coping with heat waves were used to ensure the research objectives were met effectively. This process allowed us to obtain several relevant results aligned with the set objectives, comparable in terms of applications and methodologies.

2.6. Step 4: Collection, Synthesis, and Reporting of Results

In the fourth step of the method, the results were systematically collected and compared for each of the 12 search strings, adhering to the three-phase scoping process outlined in Section 2.3.

Initially, a comprehensive collection of all relevant results was undertaken. A broad analysis was then conducted to compare key metrics, including the year of publication, number of publications, principal authors, significant keywords, and their occurrence more than five times in the results. Specifically, publication years were analyzed to trace the evolution of GI research, highlighting trends and shifts in focus, particularly concerning ecosystem service mapping and remote sensing methodologies.

According to our research objectives, the results were more carefully collected by applying filters to ensure significant outcomes for the subsequent phase. For example, we identified the top ten keywords for each string based on their occurrence, prioritized authors by publication frequency and citation impact, and identified the most prolific research centers.

After each of the three main phases, the most relevant results were extracted and compared to yield detailed insights into the methodologies and indicators utilized within the studies, as well as specific information on the ecosystem services mapped. This process allowed us to obtain several relevant results aligned with the set objectives, comparable in terms of applications and methodologies. This systematic process ensured a thorough understanding of how remote sensing technologies are applied in UGI planning, particularly in the context of mitigating heat wave hazards. Although specifically mentioned for heat waves, this approach is repeatable for all types of hazards.

3. Results

3.1. Overview of Research Activities

According to the research objectives highlighted in step one, the results were systematically organized and analyzed to address the scope of this research, transitioning from a general overview of the findings to a more specific focus on methodologies (Figures 3 and 4). In the first part of the collection of the results, we considered all three phases to examine the breadth, scope, and nature of research activities in the field of applying remote sensing technologies for UGI planning, providing a temporal and thematic overview across all relevant research studies. This analysis aimed to address the first research objective (1).



Figure 4. Results of the scoping review process across three phases.

In the first phase of analysis (Figure 3), the scoping process identified 481 relevant articles. By applying more stringent inclusion criteria in the second phase, this selection was refined to 410 articles. The final phase further narrowed the results to 325 articles, focusing on those that most closely matched this study's objectives. From these, only those with the most relevant key metrics were selected for detailed analysis, resulting in 24 highly

relevant articles being thoroughly examined in terms of methodologies and application cases (Appendices B–D).

The first phase of the scoping process examined the general concept and application of remote sensing methodologies in GI planning, reflecting large-scale projects at metropolitan and regional levels (Appendix A). The results are well-aligned with the concept of ecosystem services. However, significant interest in remote sensing only grew in 2010, showing an increasing use for mapping and monitoring UGI through spatial analyses in GIS (Figures 4 and 5).

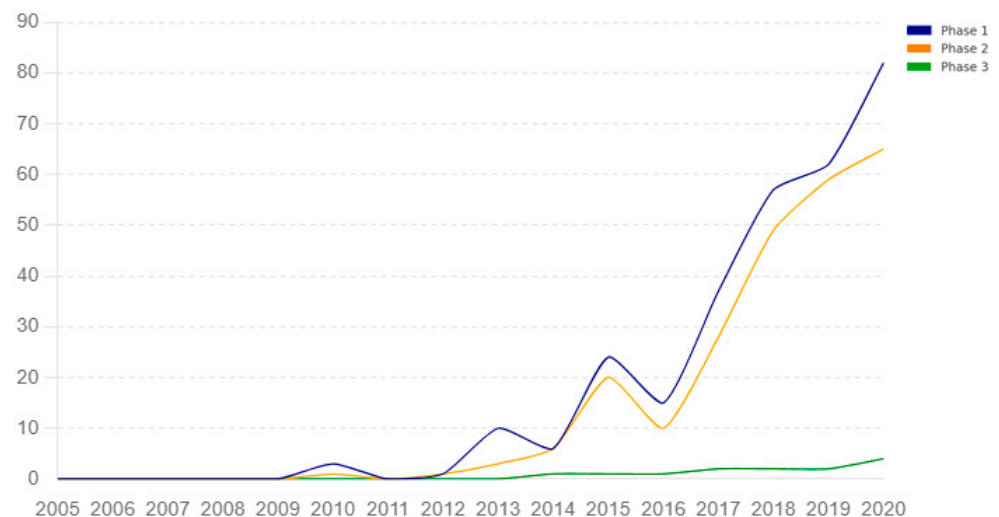


Figure 5. Temporal evolution of the results for each string by phase.

The analysis showed a generally increasing trend in research activities, with noticeable peaks in 2012, 2014, 2016, and 2019, but a decline in 2021 (Figure 5).

In the second phase, the keywords of search strings were more closely aligned with the concept of remote sensing for GI design at the urban scale. This phase emphasized the key role of interoperable analytical tools for ecosystem service modeling and scenario-based simulation. Furthermore, since 2013, there has been a greater correspondence in results related to climate change adaptation studies, as well as those addressing urban heat island effects (Figures 6 and 7).

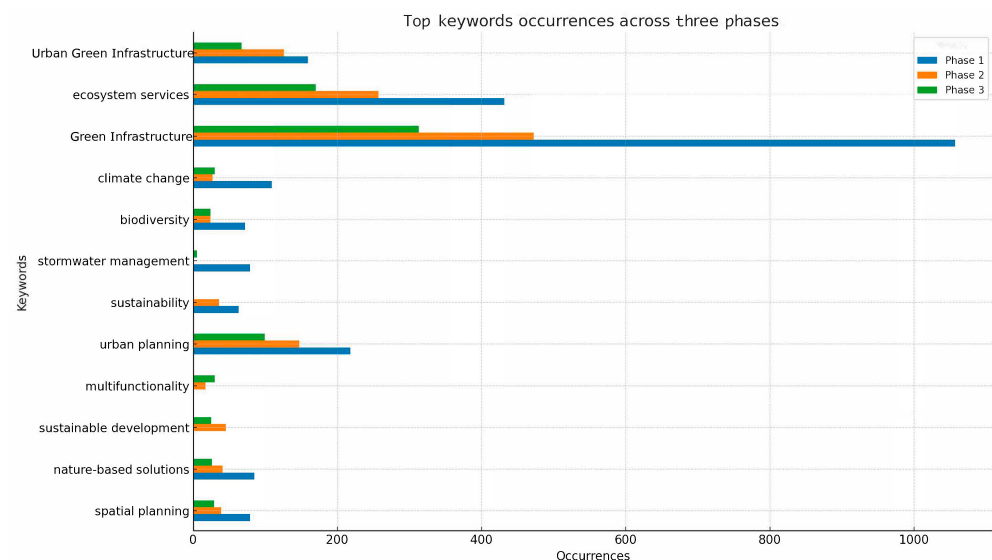


Figure 6. Top keyword occurrences across the three phases.

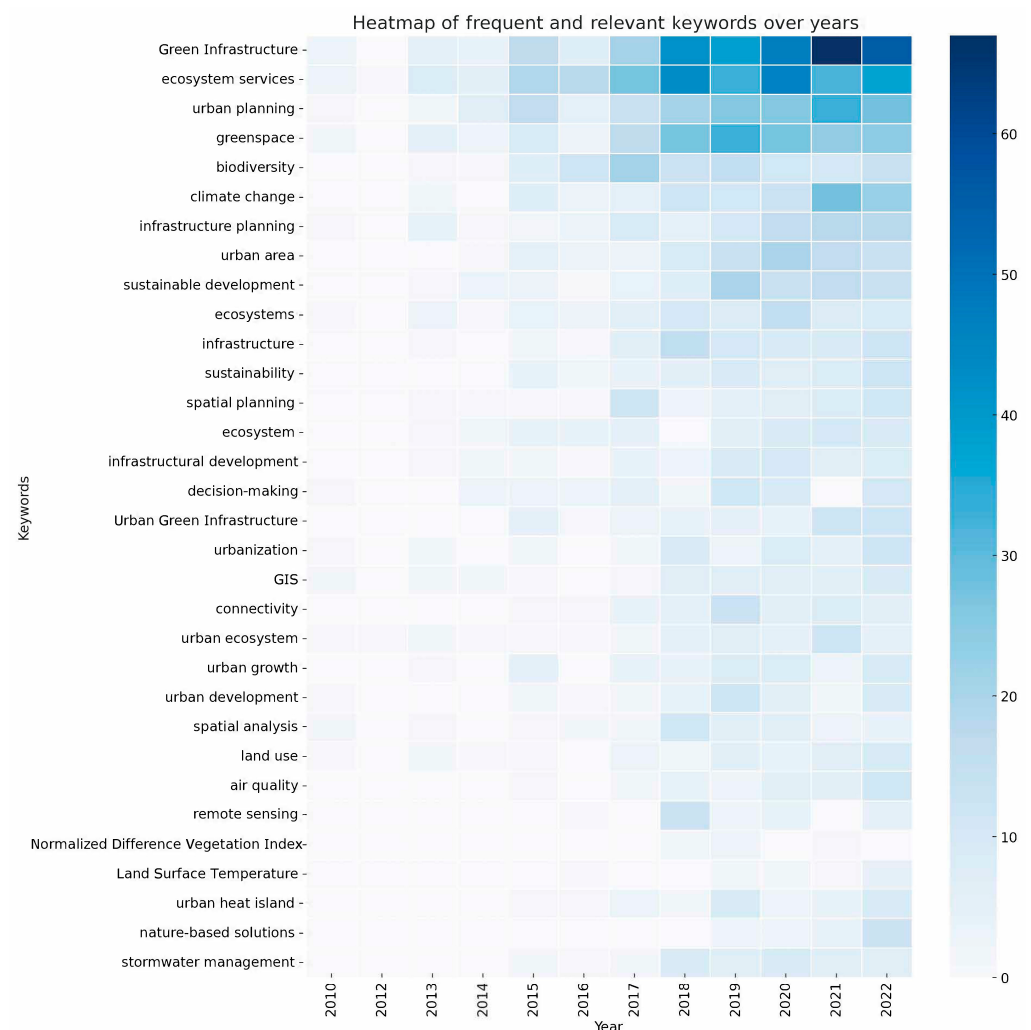


Figure 7. Heatmap of top keywords occurrences over time.

In the final phase of the keyword research process, it emerged that focusing on the keyword “heat wave” led to highly relevant results for remote sensing methodologies applied to UGI, including the occurrence of some multispectral indices widely used in the literature to analyze the response of UGI to heat wave effects, such as NDVI (Normalized Difference Vegetation Index) and LST (Land Surface Temperature). Moreover, since 2018, the results have significantly increased, indicating a high responsiveness of remote sensing technologies for climate adaptation during heat wave phenomena (Figure 7).

3.2. Applications and Methodologies

At the end of the three phases, the 24 articles most aligned with the research objectives were selected based on key metrics for a detailed analysis of the proposed methodologies and specific approaches used to map ecosystem services (Appendices B–D). These results were further analyzed to address the second and third objectives including the following:

(2) Provide a clear overview of the data-driven methodologies and ecosystem-based approaches that employ urban-scale satellite data for UGI design.

(3) Describe a research framework for the climate-adaptive design of UGI aimed at mitigating heat waves through a data-driven process using remote sensing technologies.

The aim was to provide an overview and compare the methodologies in terms of the use of indicators related to the specific hazard (Figure 8). Notably, from the general overview process, none of the identified studies span multiple scales; rather, all studies focus on individual scales of application. The scales considered include regional, urban,

and local (district). We focus on analyzing the results for each scale independently, as none of the studies employed multi-scale approaches.

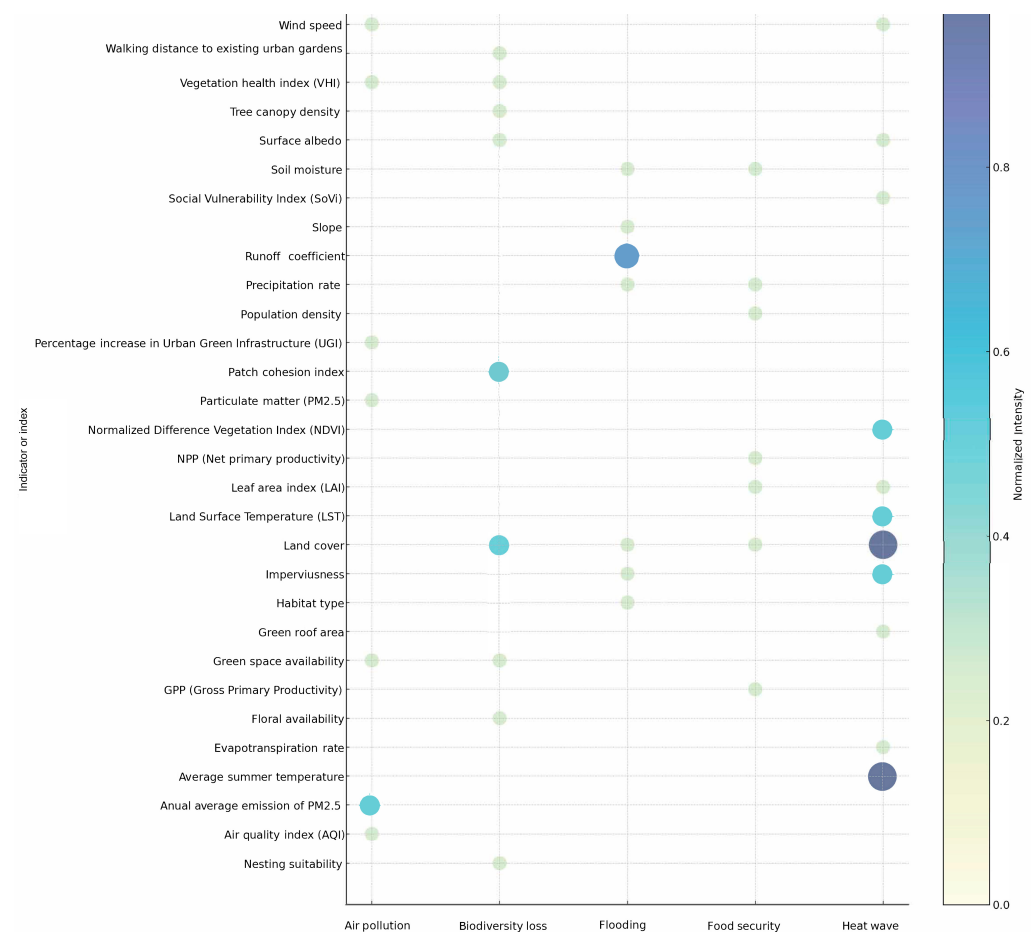


Figure 8. Bubble chart of key indicators recorded in the third phase of analysis.

3.2.1. Regional Scale Applications

In the first phase, which focused on applications at the regional and metropolitan scale, the results indicate that remote sensed technologies are predominantly used for spatial planning and ecosystem protection and management (Appendix B). The mapping objects at this scale include the supply of regulating and maintaining ecosystem services, biodiversity, and the relationships between UGIs and the health and well-being of the population [26–31]. Specifically, methodologies are employed to map phenomena such as habitat fragmentation, soil erosion, air pollution, and coastal vulnerability. At this scale, open-source satellite data with global coverage are used to map the state of natural resources and specific land transformation phenomena. The most common analytical methodologies at this level are those that integrate land cover and land use data with local data for the application of ecosystem-based dynamic models. A recurring approach in the results is the use of InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs), a tool developed by the Natural Capital Project [26]. InVEST is used to assess how different management choices affect ecosystem services, such as carbon sequestration, water purification, and coastal protection. Among the most important indicators identified in these studies are the rate of deposition of air pollutants on vegetation, erosion control, water infiltration into the soil, coastal protection capabilities, and carbon content in above-ground biomass. Land cover and land use, habitat type, plant and invertebrate diversity, and Shannon's Index (SHDI) are frequently used to assess biodiversity and landscape health. Indicators such as

slope, sediment composition, sea level changes, and storm flood potential are critical for understanding ecosystem vulnerability and resilience.

3.2.2. Urban Scale Applications

The results from the second phase pertain to the application of remote sensing methodologies at an urban scale for UGI design (Appendix C). The primary hazards include air pollution, flooding, and heat waves. The mapping objects at this scale are focused on co-benefit provision, climate regulating services, and opportunities for nature-based recreation [32–36]. These results show that mapping and monitoring methodologies based on remote sensing data at this scale are often integrated with modeling and simulation activities, especially to quantify and compare benefits and co-benefits in different design scenarios. Specific studies on air pollution demonstrate how UGI can sequester pollutants and cool urban areas, thereby improving overall urban climate regulation. Tools such as ENVI-met for three-dimensional and thermodynamic microclimate modeling, and I-Tree Eco for evaluating urban regulatory ecosystem services, have been widely used. The most used methodologies include spatial analysis based on green area and population data, on-field surveys with GPS, and air quality monitoring over extended periods. The results also indicate the use of detailed satellite data overlapped with social, demographic, and economic data to ensure a benefit-based approach. For example, studies have calculated recreational potential using the ESTIMAP-recreation model, which considers factors such as the presence of water, protected natural areas, and the degree of naturalness of the environment. The model combines recreational potential (RP) with proximity information, such as distance from roads and urban areas, to provide a comprehensive assessment. Among the most important indicators identified in these studies are carbon sequestration, daily mean temperature, and the number of pollutants captured by vegetation. These indicators are crucial for understanding the environmental benefits of UGI. Social indicators such as accessibility to public green spaces and the number of people being physically active highlight the human benefits provided by urban green areas. Additionally, indicators like the Green Area Ratio (GAR) and total green area per inhabitant help measure the extent and accessibility of green spaces in urban environments.

3.2.3. Application for Heat Wave Adaptation at the District Level

The results of the last phase, which focuses on remote sensing technologies for the climate-adaptive design of UGI, are centered on mapping the response to heat wave hazards (Appendix D). The mapping objects in this phase are more specific and include the assessment of heat exposure areas, vulnerability of different demographic groups, behavioral patterns influencing heat exposure, cooling benefits of vegetation, urban heat island intensity, social vulnerability, and access to green spaces [37–51]. Additionally, the mapping objects extend to microclimatic regulation by urban vegetation, the impacts of UGI on nighttime temperature variations, and overall well-being related to green areas. For instance, the studies examine flood control and urban cooling benefits provided by green roofs and other UGI components. The methodologies most used involve high-resolution satellite data to capture detailed site-specific information. Public and open datasets such as Sentinel-2 from Copernicus and Landsat are typically used, but for more specific applications addressing heat wave hotspots, additional commercial data and environmental sensors, including those on drones, are integrated. These sensors capture detailed environmental variations and provide precise measurements of parameters such as air temperature and humidity.

The data collected from these remote sensing technologies are often integrated with detailed demographic and census information, including population density, age distribution, health status, and hospital admissions. This integration allows for the establishment of statistically significant correlations between heat wave phenomena and the most vulnerable demographic groups.

In the context of heat wave adaptation, the most relevant indicators and indices identified in the studies include air temperature, which provides a direct measure of the thermal environment, and Land Surface Temperature (LST), which gives insights into surface heat variations. The Normalized Differential Vegetation Index (NDVI) is used to measure vegetation reflectance, distinguishing between vegetated and non-vegetated surfaces and highlighting the cooling effects of green areas. Social vulnerability indices, such as the Social Vulnerability Index (SoVi) and the Index of Relative Socio-Economic Disadvantage (IRSD), help identify populations most at risk. Additional indicators like mean and maximum air temperatures, relative humidity at 2 m, and cloud cover are essential for understanding microclimatic conditions. Urban design elements, including street width, the height-to-width ratio, and green roof area, are also considered for their impact on urban heat island (UHI) effects and overall cooling. Furthermore, social and economic factors such as the elderly population density, building energy performance, and neighborhood walkability are important for evaluating the broader implications of heat wave mitigation strategies. These indicators provide a comprehensive framework for assessing urban heat stress and the effectiveness of UGI in mitigating high temperatures, enhancing the resilience of urban environments to heat wave hazards.

4. Discussion

This scoping literature review provides critical insights into the application of remote sensing technologies for UGI planning and design, highlighting the necessity of a multiscale, integrative approach for developing proper and effective strategies. The findings align with the initial objectives and assumptions, offering a comprehensive perspective on the evolving studies. The discussion is structured to address the research questions progressively, based on the following funnel approach:

- A temporal analysis of the evolution in the field of research in relation to major guiding documents and technological advancements.
- Methodological overview at the regional scale.
- Methodological overview at the urban scale.
- Methodological overview of heat wave applications.
- Focus on emerging indicators of heat waves.

4.1. Temporal Analysis

We analyzed the trends in the three phases by comparing the most recurring keywords and then specifically examined the occurrence of keywords over the years across all results to identify the research fields that are most consolidated in the scientific literature (Figures 5 and 6). The results show that the set temporal range, along with the inclusion and exclusion criteria and the field of analysis, is appropriate. The temporal analysis (Figures 9 and 10) reveals distinct peaks in research activity that align with the release of significant policy documents, agreements, and advancements in remote sensing technology. This suggests a growing recognition of the importance of UGI mapping and monitoring for climate change mitigation and adaptation efforts, reflecting the strategic role of these analytical methodologies. Following the 2008 UNFCCC (Compendium on Methods and Tools to Evaluate Impacts of, and Vulnerability and Adaptation to, Climate Change) [52] and the Copenhagen Accord of 2009, there was an initial rise in interest, reflecting an increased interest in analytical methodologies for climate adaptation strategies. The 2010 TEEB (The Economics of Ecosystems and Biodiversity) [53] report further amplified this trend by highlighting the economic value of ecosystems. A marked surge in research activity post-2013 aligns with the EU's MAES (Mapping and Assessment of Ecosystems and their Services) strategy [54], which emphasizes the integration of ecosystem services into urban planning through comprehensive ecosystem mapping and assessment. The Paris Agreement in 2015, the launch of the Sustainable Development Goals, and the deployment of Sentinel 2A/2B satellites led to another significant peak, underscoring global commitments to climate adaptation and the enhanced capabilities of new remote sensing tools. Further intensification in

2018, driven by the IPCC's report on Global Warming of 1.5 °C and the release of Landsat 8 data, underscores the urgent need for effective and suitable adaptive measures. The European Green Deal in 2019 [54] and the EU Biodiversity Strategy in 2020 [55] sustained high research interest, reinforcing a strategic focus on sustainable urban development and ecosystem restoration.

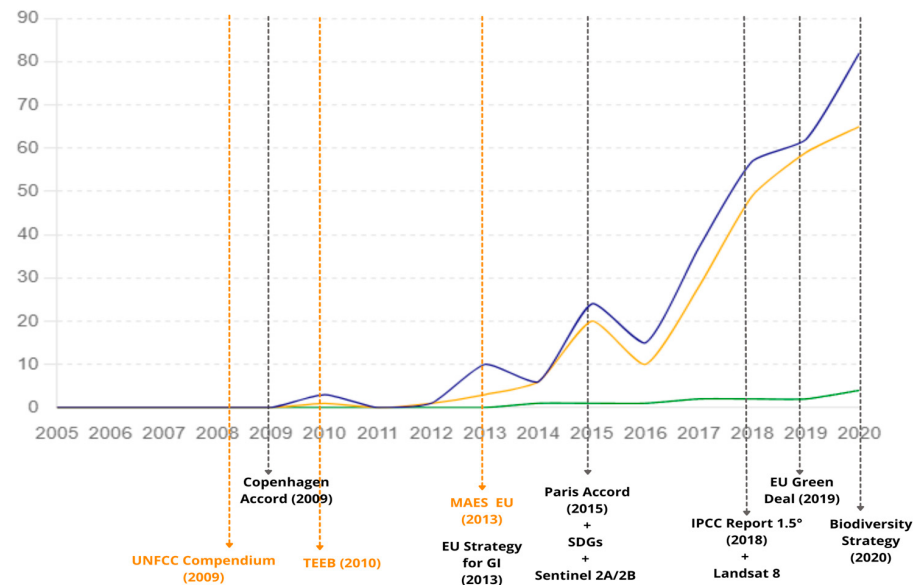


Figure 9. Temporal overview across the three phases of investigation.

Type	Sensors	Satellite	Year	Data accessibility	Institution	Spatial resolution	Temporal resolution	Possible uses for mapping and monitoring
Multispectral	Vegetation (VGT)	SPOT-4, SPOT-5	1998, 2002	On project	CNES (France)	1 km	Dayly	Natural Capital Stock, Stock Condition (woodybiomass, canopy structure) Ecosystem Services (water cycle, Primap productivity, carbon storage, woody biomass, canopy structure)
Multispectral	MERIS	ENVISAT	2002	On project	ESA	300 m, 1.2 km, 4.6 km	Dayly	
Multispectral	Landsat TM	Landsat 4-5	1982, 1984	Free	NASA/USGS	30 metri (pancromatico), 120 metri (multispettrale)	16 days	
Multispectral	Landsat ETM+	Landsat 7	1999	Free	NASA/USGS	30 metri (pancromatico), 60 metri (multispettrale)	16 days	
Multispectral	Landsat OLI-Tirs	Landsat 8	2013	Free	NASA	15m (pancromatico), 30m (multispettrale)	16 days	
Multispectral	MODIS	Terra, Aqua	1999, 2002	Free	NASA	250 metri (bande visibili), 500 metri (bande infrarosse), 1 km (banda termica)	Dayly	
Multispectral	MSI (MultiSpectral Instrument)	Sentinel-2 a/b	2015	Free	ESA	Da 10 metri a 60 metri	5 days	
Multispectral	Planet Scope	Planet Scope	2016	Commercial	Planete LAB	3 m	Dayly	
Multispectral	HRI	Pleiades	2021	Commercial	Airbus	0.5 m	On demand	
Iperspectral	Hyperion	EO-1	2000	Commercial	NASA	30 m	16 days	Ecosystem services (nitrogen)
Iperspectral	PRISMA	PRISMA	2019	On project	ASI	30 metri - 5m	16 days	
Radar	Synthetic Aperture Radar RADARSAT-1/2	RADARSAT-1/2	2007	Commercial	CSA	10x5 m	24 days	Ecosystem services (protection by coastal wetlands and magroves)
Radar	Synthetic Aperture Radar (TerraSAR X)	TerraSAR X	2008	Commercial	DLR (German Aerospace Center)	1x1 m	11 days	
Radar	PALSAR (Phased Array type L-band Synthetic Aperture Radar)	ALOS (Advanced Land Observing Satellite)	2006	Commercial	JAXA (Japan Aerospace Exploration Agency)	10x10 m	Dayly	
Radar	Synthetic Aperture Radar	Cosmo Sky-med	2010,2014	Commercial	Asi	1x1 m	1-4-8 days	
Radar	Sentinel-1	Sentinel-1A, Sentinel-1B	2014, 2016	Free	ESA	5x5 m	6-12 days	
Lidar	GLAS (Geoscience Laser Altimeter System)	ICESat (Ice, Cloud, and land Elevation Satellite)	2003	Free	NASA	70 metri (bin size)	91 days (circular)	Stock Condition (Vegetation Height)

Figure 10. Overview of remote sensing data types and purposes.

These trends indicate that key international policies and technological advancements have critically shaped the research framework, driving global efforts to integrate data-driven methodologies into climate adaptation strategies.

The keyword occurrence temporal graph (Figure 7) reveals that widely established concepts in the scientific literature, such as GI, ecosystem services, and spatial planning, appear frequently, showing steep gradients. They represent umbrella concepts that encompass the entire body of work, acting as red threads running through the scientific literature across all considered disciplines. In contrast, more specific keywords related to methodologies like remote sensing appear less frequently, indicating emerging research areas. This demonstrates the multisectoral nature and the ability to capture evolutionary processes closely tied to technological advancements, highlighting their strong dependence.

4.2. Methodological Overview of Regional-Scale Applications

The breadth and depth of research activity in remote sensing methodologies for GI planning reflect a substantial and growing body of work. The extensive use of remote sensing for spatial planning and ecosystem mapping and monitoring at regional and metropolitan scales demonstrates the versatility and scalability of these technologies. Most of the studies emphasize the importance of integrating land cover and land use data with local information to model ecosystem dynamics effectively, underscoring the potential of remote sensing to capture large-scale environmental patterns and inform regional planning decisions. Applications at this scale often do not require highly detailed satellite data and thus frequently utilize open-source products such as Sentinel-2 or Landsat 8. Moreover, significant attention is given to GI as ecological networks, with a focus on habitat restoration and conservation and phenomena such as landscape fragmentation and other spatial modification. This reflects the inherently sectoral nature of these applications, which tend to analyze specific phenomena rather than adopting a holistic view of environmental complexities, thus prioritizing specialized approaches over integrated environmental assessment.

4.3. Methodological Overview of Urban-Scale Applications

At the urban scale, theoretical and experimental methodologies reveal a growing trend toward tool interoperability. This includes tools for modeling design scenarios and simulating alternatives to assess potential benefits. This multiscale and multidisciplinary approach, reflecting the complexity of urban systems, goes beyond ecosystem mapping and monitoring strategies and supports detailed design processes. For example, studies where remotely sensed satellite data, particularly land cover, are used to feed ENVI-met models for quantifying environmental performance and I-Tree for evaluating the ecosystem services of urban greenery. This approach not only quantifies the benefits of UGIs in terms of regulation ecosystem services, such as air quality regulation, climate regulation, erosion regulation, and pollination, but also considers cultural ecosystem services, which are fundamental to the effectiveness of projects in an urban complex environment.

Such integration provides comprehensive support to UGI design and decision-making processes, addressing ecological and human factors to maximize ecological, social, and cultural benefits. While this integrated approach offers a robust framework for UGI assessment and the development of design strategies, several challenges and limitations must be acknowledged. The accuracy and resolution of remote sensing data can vary based on the technology and methodologies used, potentially impacting the reliability of results. Additionally, integrating diverse data sources requires substantial expertise in data management and analysis.

4.4. Methodological Overview for Heat Wave Adaptation

An original contribution of this study is the comparison of remote sensing methodologies for the climate-adaptive design of UGI, specifically aimed at mitigating heat waves (Appendix D). This document details recurring indicators and their respective methodolo-

gies for digitally modeling either the effects of heat waves on different population groups or the benefits, in terms of ecosystem services, achievable through the implementation of specific Green Infrastructure components, such as green roofs.

The results underscore the extensive use of high-resolution satellite data, which not only provide continuous land cover information but also crucial air and surface temperature data essential for mapping the urban heat island (UHI) phenomenon.

However, for several applications, the integration of commercial data from drone sensors and on-site environmental sensors is essential to provide detailed insights into microclimatic local conditions and heat wave hotspots. Our findings also show a significant trend toward integrating demographic and social data, enabling the identification of vulnerable groups and supporting more precise and equitable adaptation strategies. This approach reflects the initial assumption that effective UGI must adapt to both natural and anthropogenic systems, thereby enhancing urban resilience through tailored UGI strategies while ensuring they meet stakeholders' needs.

4.5. Emergent Indicator Categories

A critical component of this review is the investigation and categorization of indicators, which are essential for understanding mapping objectives and methodologies. The recorded set of indicators, representing the necessary information for the climate adaptation project for heat waves, highlighted the increasingly recognized trend in the literature to consider multiple specific hazards in project decisions (Figure 11). Therefore, we categorized the indicators to obtain further specification and ensure a comprehensive analysis, grouping them into several key categories including the following: land cover indicators, environmental performance indicators, ecosystem structure indicators, ecosystem condition indicators, social and wellbeing indicators, and land use indicators. This structured framework addresses the critical aspects of climate adaptation, ensuring a holistic and effective approach to managing urban heat waves and enhancing urban resilience.

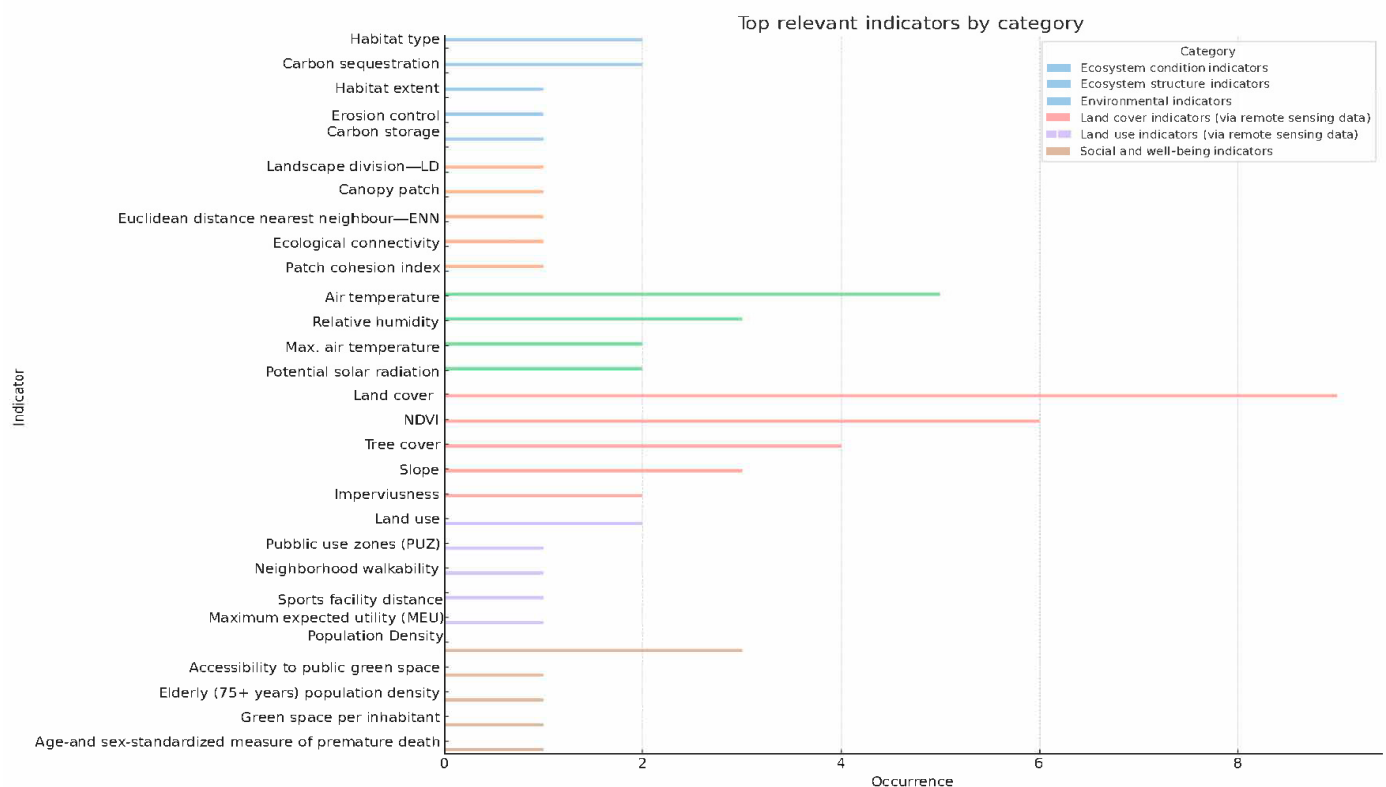


Figure 11. Comparison and classification of key indicators recorded in the third phase of the analysis.

Land cover indicators, such as NDVI, provide insights into vegetation health and connectivity, which are crucial for managing urban heat waves and evaluating green areas' effectiveness in cooling and temperature reduction. Ecosystem structure indicators, like habitat connectivity and landscape fragmentation, help identify critical areas for ecological interventions that promote biodiversity and resilience. Land use indicators inform strategic planning by classifying urban land into residential, commercial, and industrial areas, facilitating targeted UGI benefits. Social and well-being indicators, including population density and socio-economic distribution, can be integrated with environmental data to identify heat wave-vulnerable areas, ensuring policies meet local community needs. Ecosystem condition indicators, such as vegetation health and soil pollution, are used to monitor the overall state of urban ecosystems, guiding restoration and management strategies. Lastly, environmental indicators, including surface temperature and air quality, are used to assess UGIs' impacts on the urban microclimate, highlighting their role in reducing temperatures and improving air quality for healthier urban environments.

5. Conclusions

Urban Green Infrastructures have emerged as critical components in climate-adaptive urban planning and design, particularly for their role in mitigating the effects of global warming in relatively short timeframes. The effectiveness of UGIs is based on a thorough understanding of urban ecosystem dynamics, facilitated by the strategic mapping and monitoring of ecosystem services across various scales.

The integration of remote sensing data, spanning from regional to local levels, enhances our comprehension of the interplay between urban and natural environments. Advanced analytical tools play a pivotal role in this integration, enabling precise quantification of environmental performance within urban settings. This, in turn, supports informed decision-making in the development and implementation of UGIs. By combining the mapping and monitoring of ESs with modeling tools, these data-driven approaches optimize the ecological and socio-economic benefits of UGIs, thereby bolstering urban and climate resilience. Such evidence-based planning not only enhances ecological efficiency but also fosters greater community acceptance, leading to improved management of ecosystem services over time.

Despite their growing importance, the implementation of remote sensing methodologies for UGI planning and design is often complex, as it relies on non-open-source data or software, making interoperability among mapping, monitoring, modeling, and simulation tools difficult. Additionally, the availability and accessibility of data are not uniform geographically, as not all countries have adopted the same data implementation policies within dedicated platforms. Reliable and cyclically updated data are crucial for making accurate predictions regarding the impacts of specific greening interventions in urban areas. Furthermore, collaboration among public administrations and stakeholders is essential for maintaining these datasets and fostering inclusive urban planning processes. Such coordinated efforts ensure that UGIs address specific urban requirements effectively, thereby enhancing the overall performance and resilience of urban green networks. Future developments could involve the use of machine learning systems to optimize the acquisition and utilization of satellite data. Projects like AI4Copernicus aim to connect Artificial Intelligence (AI) with Earth Observation (EO), simplifying the acquisition of large quantities of EO data and promoting access to educational materials and expertise.

Author Contributions: Methodology, software, and investigation, M.D.P.; original writing, M.D.P.; conceptualization, validation, and editing M.R., M.F.L. and M.D.P. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in this study.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

SEARCH STRINGS	YEARS	N° RESULTS	KEYWORDS	OCCURENCE	RELEVANT AUTHORS (N° OF PUBLICATIONS)	RELEVANT AUTHORS (N° OF CITATIONS)
1 TITLE("GREEN INFRASTRUCTURE")	2005-2022	1,047	1 Green Infrastructure	471	Pauleit, S. (Technical University of Munich) Wang, Y. (University of Rhode Island) Angelstam, P. (Professor at Swedish University of Agricultural Sciences) Xia, B. (School of Environmental Science and Engineering, Sun Yat-sen University) Kim, G. (O-Jeong Resilience Institute (OJERI), Korea University)	- Meerow S.; Newell J.P. - Matthews T.; Lo A.Y.; Byrne J.A. - Norton B.A.; Coutts A.M.; Livesley S.J.; Harris R.J.; Hunter A.M.; Williams N.S.G. - Hansen R.; Pauleit S. - Zölch T.; Maderspacher J.; Wamsler C.; Pauleit S.
			2 ecosystem services	145		
			3 urban planning	78		
			4 Urban Green Infrastructure	56		
			5 stormwater management	51		
			6 climate change	43		
			7 sustainability	34		
			8 nature-based solutions	33		
			9 spatial planning	31		
			10 biodiversity	27		
2 TITLE("GREEN INFRASTRUCTURE"))AND ALL("ECOSYSTEM SERVICES")	2006-2022	730	1 Green Infrastructure	322	Pauleit, S. Wang, Y. Angelstam, P. Xia, B. Kim, G.	-Norton B.A.; Coutts A.M.; Livesley S.J.; Harris R.J.; Hunter A.M.; Williams N.S.G. -Meerow S.; Newell J.P. -Lovell S.T.; Taylor J.R. -Hansen R.; Pauleit S. -Andersson E.; Barthel S.; Borgström S.; Colding J.; Elmqvist T.; Folke C.; Gren A.
			2 ecosystem services	145		
			3 urban planning	73		
			4 Urban Green Infrastructure	49		
			5 climate change	34		
			6 nature-based solutions	29		
			7 spatial planning	29		
			8 stormwater management	28		
			9 biodiversity	26		
			10 sustainability	23		
3 TITLE("GREEN INFRASTRUCTURE"))AND ALL("ECOSYSTEM SERVICES")AND ALL("REMOTE SENSING OR SATELLITE DATA")	2010-2022	197	1 Green Infrastructure	68	Osmond, P. (School of Built Environment, University of New South Wales) Wang, Y. Angelstam, P. Peters, A. (University of Basel) Xia, B.	-Norton B.A.; Coutts A.M.; Livesley S.J.; Harris R.J.; Hunter A.M.; Williams N.S.G. -Meerow S.; Newell J.P. -Zölch T.; Maderspacher J.; Wamsler C.; Pauleit S. -Wickham J.D.; Riitters K.H.; Wade T. G.; Vogt P. -Chen W.Y.
			2 ecosystem services	36		
			3 urban planning	20		
			4 Urban Green Infrastructure	15		
			5 climate change	12		
			6 GIS	9		
			7 nature-based solutions	7		
			8 connectivity	7		
			9 climate change adaptation	6		
			10 sustainability	6		
4 TITLE("GREEN INFRASTRUCTURE"))AND ALL("ECOSYSTEM SERVICES")AND ALL("REMOTE SENSING OR SATELLITE DATA") OR ALL("MAPPING"OR"MONITORING")	2010-2022	481	1 Green Infrastructure	196	Pauleit, S. Wang, Y. Angelstam, P. Olfsson, A.S. (University of Copenhagen) Xia, B.	-Norton B.A.; Coutts A.M.; Livesley S.J.; Harris R.J.; Hunter A.M.; Williams N.S.G. -Meerow S.; Newell J.P. -Lovell S.T.; Taylor J.R. -Hansen R.; Pauleit S. -Zölch T.; Maderspacher J.; Wamsler C.; Pauleit S.
			2 ecosystem services	106		
			3 urban planning	47		
			4 Urban Green Infrastructure	39		
			5 climate change	20		
			6 biodiversity	19		
			7 connectivity	19		
			8 spatial planning	19		
			9 nature-based solutions	16		
			10 GIS	15		

Figure A1. Research string used in phase 1.

SEARCH STRINGS	YEARS	N° RESULTS	KEYWORDS	OCCURENCE	RELEVANT AUTHORS (N° OF PUBLICATIONS)	RELEVANT AUTHORS (N° OF CITATIONS)
5AND ALL("URBAN AREAS"OR"URBAN ECOSYSTEM"AND"GREEN AREAS")OR ALL("URBAN GREEN INFRASTRUCTURE")	2010-2022	335	1 Green Infrastructure	127	Pauleit, S. Olafsson, A.S. Wang, Y. Xia, B. Ni, Z. (South China Agricultural University)	-Norton B.A.; Coutts A.M.; Livesley S.J.; Harris R.J.; Hunter A.M.; Williams N.S.G.; -Meerow S.; Newell J.P. -Lovell S.T.; Taylor J.R. -Zölch T.; Maderspacher J.; Wamsler C.; Pauleit S. -Jayasooriya V.M.; Ng A.W.M.; Muthukumar S.; Perera B.J.C.
			2 ecosystem services	71		
			3 urban planning	40		
			4 Urban Green Infrastructure	39		
			5 sustainable development	14		
			6 nature-based solutions	13		
			7 climate change	13		
			8 spatial planning	11		
			9 biodiversity	11		
			10 sustainability	11		
6AND ALL("URBAN AREAS"OR"URBAN ECOSYSTEM"AND"GREEN AREAS")OR ALL("URBAN GREEN INFRASTRUCTURE")OR ALL("URBAN ECOSYSTEM SERVICES")	2010-2022	371	1 Green Infrastructure	148	Pauleit, S. Olafsson, A.S. Wang, Y. Xia, B. Ni, Z.	-Norton B.A.; Coutts A.M.; Livesley S.J.; Harris R.J.; Hunter A.M.; Williams N.S.G.; -Meerow S.; Newell J.P. -Lovell S.T.; Taylor J.R. -Zölch T.; Maderspacher J.; Wamsler C.; Pauleit S. -Jayasooriya V.M.; Ng A.W.M.; Muthukumar S.; Perera B.J.C.
			2 ecosystem services	78		
			3 urban planning	43		
			4 Urban Green Infrastructure	39		
			5 sustainable development	16		
			6 spatial planning	14		
			7 climate change	14		
			8 nature-based solutions	13		
			9 sustainability	12		
			10 GIS	12		
7AND ALL("URBAN AREAS"OR"URBAN ECOSYSTEM"AND"GREEN AREAS")OR ALL("URBAN GREEN INFRASTRUCTURE")OR ALL("URBAN ECOSYSTEM SERVICES")AND ALL("DESIGN"OR"PROJECT")	2010-2022	381	1 Green Infrastructure	164	Pauleit, S. Olafsson, A.S. Osmond, P. Wang, Y. Ni, Z.	-Norton B.A.; Coutts A.M.; Livesley S.J.; Harris R.J.; Hunter A.M.; Williams N.S.G.; -Meerow S.; Newell J.P. -Lovell S.T.; Taylor J.R. -Hansen R.; Pauleit S. -Zölch T.; Maderspacher J.; Wamsler C.; Pauleit S.
			2 ecosystem services	76		
			3 urban planning	49		
			4 Urban Green Infrastructure	35		
			5 sustainable development	15		
			6 nature-based solutions	15		
			7 spatial planning	14		
			8 multifunctionality	13		
			9 biodiversity	13		
			10 sustainability	13		
8AND ALL("URBAN AREAS"OR"URBAN ECOSYSTEM"AND"GREEN AREAS")OR ALL("URBAN GREEN INFRASTRUCTURE")OR ALL("URBAN ECOSYSTEM SERVICES")AND ALL("DESIGN"OR"PROJECT")OR ALL("MODELING"OR"SIMULATION")	2010-2022	410	1 Green Infrastructure	33	Pauleit, S. Olafsson, A.S. Wang, Y. Ni, Z. Osmond, P.	-Norton B.A.; Coutts A.M.; Livesley S.J.; Harris R.J.; Hunter A.M.; Williams N.S.G.; -Meerow S.; Newell J.P. -Lovell S.T.; Taylor J.R. -Hansen R.; Pauleit S. -Zölch T.; Maderspacher J.; Wamsler C.; Pauleit S.
			2 ecosystem services	32		
			3 urban planning	15		
			4 Urban Green Infrastructure	13		
			5 climate change adaptation	4		
			6 urban heat island	4		
			7 urban greening	4		
			8 multifunctionality	4		
			9 resilience	4		
			10 social-ecological systems	3		

Figure A2. Research string used in phase 2.

SEARCH STRINGS	YEARS	N° RESULTS	KEYWORDS	OCCURENCE	RELEVANT AUTHORS (N° OF PUBLICATIONS)	RELEVANT AUTHORS (N° OF CITATIONS)
9AND ALL("CLIMATE" AND "ADAPTATION" OR "CLIMATE ADAPTIVE DESIGN"OR "CLIMATE PROOF")	2013-2022	231	1 green infrastructure	40	Pauleit, S. Gerlak, A.K.(School of Geography, Development & Environment, university of Arizona) Meerow, S.(School of Geographical Sciences and Urban Planning, Arizona State University) Badiu, D.L. (University of Bucharest) Barton, D.N. (Norwegian Institute for Nature Research NINA)	-Norton B.A.; Coutts A.M.; Livesley S.J.; Harris R.J.; Hunter A.M.; Williams N.S.G. -Meerow S.; Newell J.P. -Zölch T.; Maderspacher J.; Wamsler C.; Pauleit S. -Jayasooriya V.M.; Ng A.W.M.; Muthukumar S.; Perera B.J.C.
			2 ecosystem services	29		
			3 urban planning	15		
			4 urban green infrastructure	7		
			5 resilience	6		
			6 climate change adaptation	6		
			7 multifunctionality	6		
			8 stormwater management	5		
			9 spatial planning	4		
			10 connectivity	4		
10 AND ALL("CLIMATE" AND "ADAPTATION" OR "CLIMATE ADAPTIVE DESIGN"OR "CLIMATE PROOF")AND ALL("VULNERABILITY" OR "RISK")	2013-2022	299	1 green infrastructure	130	Pauleit, S. Cilliers, S.S.(North-West University, Potchefstroom) Gerlak, A.K. Haase, D. (Landscape Ecology, Humboldt University) Meerow, S.	-Norton B.A.; Coutts A.M.; Livesley S.J.; Harris R.J.; Hunter A.M.; Williams N.S.G.; -Meerow S.; Newell J.P. -Lovell S.T.; Taylor J.R. -Zölch T.; Maderspacher J.; Wamsler C.; Pauleit S. -Jayasooriya V.M.; Ng A.W.M.; Muthukumar S.; Perera B.J.C.
			2 ecosystem services	66		
			3 urban planning	42		
			4 urban green infrastructure	24		
			5 climate change	15		
			6 nature-based solutions	13		
			7 multifunctionality	12		
			8 spatial planning	12		
			9 biodiversity	12		
			10 sustainable development	12		
11 AND ALL("CLIMATE" AND "ADAPTATION" OR "CLIMATE ADAPTIVE DESIGN"OR "CLIMATE PROOF")AND ALL("VULNERABILITY" OR "RISK")OR ALL("REGULATING ECOSYSTEM SERVICES" OR "CLIMATE MICRO REGULATION" OR "COOLING")	2013-2022	325	1 green infrastructure	135	Pauleit, S. Wang, Y. Ni, Z. Osmond, P. Xia, B.	-Norton B.A.; Coutts A.M.; Livesley S.J.; Harris R.J.; Hunter A.M.; Williams N.S.G.; -Meerow S.; Newell J.P. -Lovell S.T.; Taylor J.R. -Zölch T.; Maderspacher J.; Wamsler C.; Pauleit S. -Jayasooriya V.M.; Ng A.W.M.; Muthukumar S.; Perera B.J.C.
			2 ecosystem services	70		
			3 urban planning	42		
			4 urban green infrastructure	30		
			5 climate change	15		
			6 spatial planning	13		
			7 sustainable development	13		
			8 nature-based solutions	13		
			9 multifunctionality	12		
			10 biodiversity	12		
12 ...AND ALL("HEAT WAVE")	2014-2023	28	1 green infrastructure	8	Reinwald, F. (Institute of Landscape Planning, University of Natural Resources and Life Sciences, Vienna, Austria) Damjanovic, D. Marando, F. Osmond, P. Ring, Z.	-Norton B.A.; Coutts A.M.; Livesley S.J.; Harris R.J.; Hunter A.M.; Williams N.S.G.; -Saaroni H.; Amorim J.H.; Hiemstra J.A.; Pearlmuter D. -Marando F.; Salvatori E.; Sebastiani A.; Fusaro L.; Manes F. -Zardo L.; Geneletti D.; Pérez-Soba M.; Van Eupen M. -Madureira H.; Andresen T.
			2 urban green infrastructure	6		
			3 urban heat island	5		
			4 ecosystem services	5		
			5 land surface temperature	4		
			6 climate change adaptation	4		
			7 urban planning climate change	4		
			8 normalized difference vegetation index	3		
			9 remote sensing	2		
			10 urban trees	2		

Figure A3. Research string used in phase 3.

Appendix B

Bibliographic Ref.	Authors	Title	Year	Citation Index	Specific hazard	Mapping Object	Analytic Methodologies	Indicator or Index	Application case
27	Hansen R.; Pauleit S.	From multifunctionality to multiple ecosystem services? A conceptual framework for multifunctionality in green infrastructure planning for urban areas	2014	430	No specific hazard	—	Literature review.	—	—
28	Liquete C.; Kleeschulte S.; Dige G.; Maes J.; Grizzetti B.; Olah B.; Zulian G.	Mapping green infrastructure based on ecosystem services and ecological networks: a pan-european case study	2015	197	Flooding, habitat fragmentation, soil erosion, air pollution	Regulating and maintenance ecosystem services supply	Direct conversion of land use/cover maps using local data and dynamic ecosystem models. Identify and map biophysical proxies for ecosystem services based on published scientific models.	Rate deposition of air pollutants on vegetation Erosion control Infiltration of water into the soil Coastal protection capabilities Relative pollination potential Theoretical ecosystem potential Nitrogen retention efficiency in stream Carbon content in above-ground biomass	Europe
29	Connop S.; Vandergert P.; Eisenberg B.; Collier M.J.; Nash C.; Clough J.; Newport D.	Renaturing cities using a regionally-focused biodiversity-led multifunctional benefits approach to urban green infrastructure	2016	172	Biodiversity loss	Biodiversity	The paper describes a conceptual framework for the functional role of green infrastructure in urban areas, developed during the research phase of the FP7 TURAS project in collaboration with local authority planners. The analytical methodologies are not specified.	Land cover Habitat type Plant diversity Invertebrate diversity	London, Germany
30	Dennis M.; Barlow D.; Cavan G.; Cook P.A.; Gilchrist A.; Handley J.; James P.; Thomon J.; Tzoulas K.; Wheeler C.P.; Lindley S.	Mapping Urban Green Infrastructure: a novel landscape-based approach to incorporating land use and land cover in the mapping of human-dominated systems	2018	65	Health threat	Relationships between UCI and the health and well-being of the population	Using Copernicus Sentinel S2A data. Improve classification accuracy by incorporating tree canopy data and water data from other sources. Converting OS Mastermap Greenspace Layer to 10m raster cells for compatibility. Integration of land use data by the U.K. Ordnance Survey with a land cover classification derived from high-resolution satellite imagery. Calculation of landscape indices (diversity, connectivity) using the QGIS Landscape Ecology Leco5 2.0.7 plugin. Statistical comparison with existing datasets (Urban Atlas 2012, LCM 2015, OS Mastermap Greenspace Layer 2017) for validation. Data obtained through demographic and health data available for the different study areas (such as the Lower Super Output Areas—LSOAs).	Land cover Land use Shannon's Index—SHDI Landscape division—LD Canopy patch Euclidean distance nearest neighbour—ENN Age—and sex—standardized measure of premature death English index of multiple deprivation	Greater Manchester
31	Ruckelshaus M. H.; Guannel G.; Arkema K.; Verutes G.; Griffin R.; Guerry A.; Silver J.; Faries J.; Brenner J.; Rosenthal A.	Evaluating the benefits of Green Infrastructure for coastal areas: location, location, location	2016	41	Coastal erosion, flooding	Coastal vulnerability	InVEST model Coastal Protection.	Land cover Slope Sediment composition Sea level changes Exposure to waves Storm flood potential Social exposure Wave height and period Natural habitats Wind speed Storm duration	Gulf of Mexico

Figure A4. Results of applying of remote sensing technologies for mapping and monitoring GI. The bibliographic references are listed in the first column and can also be found in the bibliography.

Appendix C

Bibliographic Ref.	Authors	Title	Year	Citation Index	Specific hazard	Mapping Object	Analytic Methodologies	Indicator or Index	Application case
32	Christopher M. Raymonda, Niki Frantzeskaki, Nadja Kabisch, Pam Berry, Margaretha Breil, Mihai Razvan Nita, Davide Geneletti, Carlo Calapiet	A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas	2017	514	Air pollution, flooding, heat wave, habitat fragmentation	Co-benefit providing	The paper does not present analytical methodologies but rather a theoretical framework for the evaluation of NBS according a six step methodology.	Carbon sequestration Flood peak reduction Daily mean temperature Daily temp. variation Accessibility to public green space Amount of pollutants captured by vegetation Ecological connectivity Number of people being physically active Net additional jobs	No specific application case
33	Francesc Baró, Lydia Chaparro, Erik Gómez-Baggethun, Johannes Langemeyer, David J. Nowak, Jaume Terradas	Contribution of ecosystem services to air quality and climate change mitigation policies: the case of urban forests in Barcelona, Spain	2016	285	Air pollution	Climate regulating services	GIS analysis of Barcelona municipal territory. Calculation based on green area and population data. On-field survey with GPS. Air quality monitoring during 2001-2011. Estimation based on energy consumption in sectors. I-Tree Eco (formerly UFORE). Assessment based on emission and concentration data.	Total green area Green space per inhabitant Number of street trees Pollutant concentrations CO2 equivalent emissions Air purification Carbon storage Carbon sequestration Air pollution from BVOC emissions Urban forest contribution to air quality and climate mitigation	Barcelona, Spain
34	Jayasooriya V.M.; Ng A.W.M.; Muthukumaran S.; Perera B.J.C.	Green infrastructure practices for improvement of urban air quality	2017	181	Air pollution	Co-benefit providing	Plot simple on land cover map. I-Tree Eco (formerly UFORE).	Green area ratio (GAR) Equivalent annual cost (EAC) Building energy savings Hourly dry deposition of pollutants from trees for O3, SO2, NO2, CO, PM2.5 and PM10 per year	No specific application case
35	Artmann M.; Kohler M.; Meinel G.; Gan J.; Ioja I.-C.	How smart growth and green infrastructure can mutually support each other — A conceptual framework for compact and green cities	2019	168	Urban sprawl	Compact city and smart green city	The paper does not present analytical methodologies but rather a theoretical framework.	Land use Built-up areas Population density Accessibility to urban areas	No specific application case
36	Cortinovis C.; Zulian G.; Geneletti D.	Assessing nature-based recreation to support urban green infrastructure planning in Trento (Italy)	2018	52	Not specified	Capacity and opportunities for nature-based recreation	Determined using the ESTIMAP recreation model considering factors such as the presence of water, protected natural areas and the degree of naturalness of the environment. Calculated with ESTIMAP-recreation model by combining Recreational potential (RP) with proximity information, such as distance from roads and urban areas.	Recreational potential (RP) Recreational opportunity spectrum (ROS)	Trento, Italy

Figure A5. Results of applying remote sensing technologies for mapping, modeling, and simulation of UGI at the urban scale. The bibliographic references are listed in the first column and can also be found in the bibliography.

Appendix D

Bibliographic	Authors	Title	Year	Citation Index	Specific hazard	Mapping Object	Analytic Methodologies	Indicator or Indices	Application case
37	Norton B.A.; Coutts A.M.; Livesley S.J.; Harris R.J.; Hunter A.M.; Williams N.S.G.	Planning for cooler cities: A framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes	2015	640	Heat wave	Heat exposure	Heat exposure was assessed using high-resolution (0.5 m) airborne thermal remote sensing data for solar noon and midnight the during an EHE (daytime max. 37.1 °C/overnight minimum 24.7 °C) (Coutts & Harris, 2013). The data were corrected for emissivity effects and then averaged for each statistical area to identify hot spots.	Air temperature	Port Phillip, Melbourne, Australia
						Vulnerability	Demographic Information from Australian census.	Land surface temperature	
						Behavioral exposure	Local knowledge can be supplemented with information on planning zones.	Vulnerability index	
						Cooling value	A combination of visual surveys, aerial imagery, LiDAR data, GIS databases.	Index of relative socio-economic disadvantage (IRSD)	
							Created a detailed land cover map using multiscaner and LiDAR data.	Public use zones (PUZ)	
							Supervised classification in GIS software to identify seven land cover classes as follow: vegetation (trees), irrigated and non-irrigated green spaces, roofs, concrete, asphalt (roads), and water.	Street width	
							Vegetation health information were obtained from remotely sensed data or on-ground surveys.	Orientation	
38	Meerow S.; Newell J.P.	Spatial planning for multifunctional green infrastructure: growing resilience in Detroit	2017	483	Flooding	Stormwater	Rational Method (Molvany, 1850) through land use layer height resolution from SEMCOG data.	Height—to—width ratio	Detroit, USA
					Heat wave	Social vulnerability	Derived from NOAA and other resources.	Land cover	
						Access to green space	Pandas for Network Analysis (Pandana) from SEMCOG data.	Stormwater runoff	
						Urban heat island	MODIS + Google earth Engine API.	Normalized difference vegetation index (NDVI)	
						Air pollution	HR spatial air pollution model by Batterman and Ganguly 2012.	Runoff coefficient	
39	Zölch T.; Madersbacher J.; Wamsler C.; Pauleit S.	Using green infrastructure for urban climate-proofing: An evaluation of heat mitigation measures at the micro-scale	2016	228	Heat wave	Biodiversity loss	Fragstat model with land cover data and geospatial modelling environment.	CSO waste water discharges (location and volume)	Munich, Germany
						Landscape connectivity	ENVI—met V4 model with Ludwig—Maximilians—Universität München weather station, located near the case area, and climate change projections of the regional climate model REMO.	Social Vulnerability Index (SoVi)	
40	Langemeyer J.; Wedgwood D.; McPhearson T.; Baró F.; Markon A.L.; Barton D.N.	Creating urban green infrastructure where it is needed—A spatial ecosystem service-based decision analysis of green roofs in Barcelona	2020	96	Heat wave, flooding, biodiversity loss, food safety	Green roof of GI	Mapping in GIS from raster files to the HUGIN plugin.	Park poverty	Municipality of Barcelona, Spain
						Urban heat island intensity	Model by Martin-Vide et al (2015) for calculating UHL.	Land surface temperatures	
						Heat vulnerability	A heat vulnerability map from the City of Barcelona, evaluated by the Public Health Agency, classified the city into five categories (very low to very high). These categories were scaled linearly to FS demand in HUGIN.	Annual average emission of PM2.5	
						Stormwater runoff	Runoff coefficients were assigned according to Corine Land Cover classes and four soil permeability levels. To enhance resolution, the detailed Land Cover Map of Catalonia (2009) was used, matching land cover to Corine classes (EEA, 2017). Updated land use covers were then assigned average runoff coefficients from the four Corine permeability levels.	Elderly (75+ years) population density	
								Building energy performance	
								Low educational attainment	
						Pollinator habitat	ESTIMAP pollination model on Corine land cover classes and Land Cover Map of Catalonia.	Runoff coefficient	
								Land cover	
								Soil permeability	
						Food production and demands	ArcGIS was used to create 300m buffer service areas using a map of walkable Barcelona streets from OpenStreetMap (OSM, 2018). To evaluate relative demand in HUGIN, a distance decay function was adapted from Giles-Corti and Donovan (2002). A Catalonia map from IDESCAT (2016) visualized population distribution in a multiresolution grid (62.5, 125, and 250 m) using the quadtree method of Lagonigro et al. (2017). The population density raster was classified into nine groups with a one-half standard deviation range and a null class for zero inhabitants.	Slope	
								Rainfall intensity	
								Walking distance to existing urban gardens	
						Recreational opportunities	Proxy-based models with variables such as land use and network form (Lefebvre-Ropars et al., 2017), walkability can be accurately assessed via tabulating 'proximity journeys' of under 10 min that are typically local and non-motorized.	Population density	
								Grocery store per neighborhood	
								Neighborhood walkability	
41	Venter Z.S.; Krog N.H.; Barton D.N.	Linking green infrastructure to urban heat and human health risk mitigation in Oslo, Norway	2020	77	Heat wave	Urban heat island	Network walking distance was calculated in ArcGIS using 100 m and 500 m service area buffers around sport facility locations.	Sports facility distance	Oslo, Norway
							Calculated for each census tract by dividing the green area by total tract area.	Normalized difference vegetation index (NDVI)	
							Statistic, which combined Gross Family Income with education level, employment, car ownership, and real estate prices (BCN, 2016).	Neighborhood greenness	
							Nationality statistics were used in lieu of ethnicity data, which is not collected in Spain. The 178 nationalities present in Barcelona are grouped into ten cultural clusters per the GLOBE study (House et al., 2004; Mensah and Chen, 2013).	Available family income (RFI)	
							Multiple-criteria decision analysis with HUGIN plugin in Researcher v8.6.	Ethnic heterogeneity	
41	Venter Z.S.; Krog N.H.; Barton D.N.	Linking green infrastructure to urban heat and human health risk mitigation in Oslo, Norway	2020	77	Heat wave	Urban heat island	Land Cover Classification with Landsat 8 data. Using Sentinel-1 (radar) and Sentinel-2 (optical) satellite data for soil classification. Fusion of radar and optical data were used to increase classification accuracy.	Ecosystem services demand index	Oslo, Norway
							Used tree cover data from Hanssen et al. (2019) obtained from LiDAR data.	Maximum expected utility (MEU)	
							Random Forest Algorithm and Averaging NDVI from Sentinel-2 Images.	Land cover	
							Collection of public health data relating to citizens N70 years. Used data on doctor visits and hospital admissions related to heat-related health problems.	Tree cover	
41	Venter Z.S.; Krog N.H.; Barton D.N.	Linking green infrastructure to urban heat and human health risk mitigation in Oslo, Norway	2020	77	Heat wave	Urban heat island		Normalized difference vegetation index (NDVI)	Oslo, Norway
								Reduced of days at risk of heat for elderly people (75 years)	
								Reduced of morbidity and mortality	

Figure A6. Results of the application of remote sensing technologies for climate adaptation project for the heat wave. The bibliographic references are listed in the first column and can also be found in the bibliography.

42	Maranda F.; Hens M.P.; Zulfan G.; Uddas A.; Mentaschi L.; Chrysoulaki N.; Parasitidis D.; Maes J.	Urban heat island mitigation by green infrastructure in European functional urban areas	2022	71	Heat wave	Cooling in urban functional areas	Landsat 8, OLI TIRS through the use of the algorithm of Parasitidis et al. (2017), Google Earth Engine (GEE). A global emissivity map, MODIS LST emissivity data, and NDVI based. Dataset developed by the University of Colorado Denver Global Human Settlement layer population density dataset for 2015.	Land surface temperature (LST)	Barcelona, Spain; Leipzig, Germany and Trento, Italy
							Maximum air temperature		
							Population density		
							Tree cover density		
							Microclimate mitigation model based on a double linear regression: the first to estimate LST using tree cover density and water evaporation from tree bushes, and the second to estimate the operating maximum air temperature of LST and latitude.	Latitude Evaporation of water from trees	
Cooling driver analysis.							Cooling index		
43	Simon Farrugia, Malcolm D. Hudson, Lindsay McCulloch	An evaluation of flood control and urban cooling ecosystem services delivered by urban green infrastructure	2013	71	Heat wave, flooding	Flood control and urban cooling	Modification of the Ordnance Survey surface types based on the JNCC Phase 1 Habitat mapping system (JNCC 2010). Defined by visible ecological boundaries (Pagan et al. 1999) that make species migration between habitats difficult. Mapped in six selected sites. Locations recorded on-site and verified with aerial imagery from Google Earth (Google Earth 2011).	Habitat type Habitat extent Individual trees	Southampton, United Kingdom
							Assumed to be 11.31 m, based on calculations from nine British broadleaf tree species by Henry et al. (2005). Measured in parks and squares using 19 microclimate sensors with data loggers (Buttons [®]) placed at 3 m height in street lamps.	Tree crown diameter Temperature and humidity	
							Characterized manually in circular areas (buffers) around the sensors using high-resolution satellite imagery (WorldView-2). Calculated using a digital surface model with a spatial resolution of 2 m and the "area solar radiation" tool in ArcMap. Calculated from the Sentinel-2A multispectral image with a spatial resolution of 10 m using the Sen2Cor plugin in SNAP software.	Land cover types Potential solar radiation Normalized difference vegetation index (NDVI)	
							Measured in parks and squares using 19 microclimate sensors with readings every 10 minutes and hourly averages.	Land cover Air temperature Humidity Potential solar radiation Isobuilding heights Tree canopy	
							Calculated for the four locations and surrounding areas using a digital surface model Calculated from Sentinel-2A multispectral imagery (10m spatial resolution) using reflectance in red and near-infrared bands. Determined through IDW interpolation to assess how temperature and humidity vary with distance from measurement points.	Normalized difference vegetation index (NDVI) Influence distance	
44	Filipa Gallo A., Pedro Pinho A., Cristiana Aleixo A., Cristina Cafta B., Patricia Silva C., Nuno Lopes C., Catarina Freitas C., Margarida Santos-Reis A., Timon McPherson D.E., Cristina Branquinho A.,	Using green to cool the grey: modelling the cooling effect of green spaces with a high-spatial resolution	2020	56	Heat wave	Microclimatic regulation from urban vegetation	Use Generalized Linear Models (GLM) with independent variables, including the area of each land-cover type at different distances, potential solar radiation, and NDVI value	Leaf cover type	Almada, Portugal
							Calculated using ENVI 5.3 software from hyperspectral data (160 spectral bands at 2m spatial resolution) Use FRAGSTATS 4.2 software and LIDAR Satellite Data to extract medium (shrubs) and high (trees) vegetation polygons	Normalized Difference Vegetation Index (NDVI) Related circumscribing circle Normalized landscape shape index (nLSI)	
							Based on the imperviousness thresholds, the type of coverage and water supply deriving from LIDAR for the extraction of the polygons of buildings and vegetation, high resolution aerial images for validation	Green Infrastructure typology (GIT)	
							Estimated using a FLIR SC series camera with spatial resolution of 0.5m and thermal resolution of 0.08 K. Orthorectification and geometric corrections applied via PARGE software, atmospheric corrections performed via ATCOR 4 software. Thermal infrared (TIR) data obtained through an aerial survey campaign were used.	Land surface temperatures	
							LIDAR data collection with Leica ALS560-II scanner sensor at an altitude of 150m. obtained from datasets and projected onto GDA 1994 MGA Zone 56 coordinates	Slope Land registry properties	
45	Bartoszko-Koc C., Osmond P., Peters A.	Mapping and classifying green infrastructure typologies for climate-related studies based on remote sensing data	2019	50	Heat wave	Green Infrastructure components	VNIR1600 camera, capturing radiance values for 160 spectral bands at a 2 m resolution. ATCOR 4 software corrected atmospheric effects, while PARGE software performed	Land cover Tree coverage percentage Roof temperatures Road temperatures	Sydney, Australia
							Thermal data were collected with a FLIR SC Series Camera. ArcGIS 10.1 was used to analyze the cooling effects of different land cover classes. Statistical analysis, including multiple regression models, was conducted using R Software v2.13.0 to examine variable relationships.	Park temperatures	
46	Brenda B. Lin, Jacqui Meyers, R. Matthew Beatty and Guy B. Bennett	Urban Green Infrastructure Impacts on climate regulation services in Sydney, Australia	2016	37	Heat wave	Urban cooling			Sydney Urban Center (transect)
47	Santamouris M.; Osmond P.	Increasing green infrastructure in cities: impact on ambient temperature, air quality and heat- related mortality and morbidity	2020	23	Heat wave, air pollution	Impacts of UGI	Literature Review of 39 Case studies using statistical correlation.	Percentage increase of Urban Green Infrastructure Maximum peak daily temperature drop Maximum peak night-time temperature drop Heat-related mortality percentage decrease Urban pollutant concentration	-
								Imperviousness	
								Edge Size Edge-to-area ratio	
								Floor space index	
								Floor space index within a buffer of 500 m	
48	Rost, Annemarie Tabou, Lise, Victoria, Seidel, Corinna, Matschereth, Lea, Otto, Marco, Meier, Fred; Femmer, Daniel	How cool are allotment gardens? A case study of nocturnal air temperature differences in Berlin, Germany	2020	20	Heat wave	Nighttime temperature variations in different areas of Berlin with focus on allotment gardens	Field measurements and use of unspecified methodologies	Degree of sealed surface Distance from the city center	Berlin, German
							Physical measuring devices placed within the garden plots and other specific locations within the city of Berlin were used. Elaboration with Easy Log EL-USB-2.	Air temperature	
							The SVF was calculated for each site from a fish-eye photo (taken at a height of 1.20 m in July with full foliage) using the ArcGIS 10.1 software.	Sky view factor (SVF)	
49	Ring Z.; Dampjanovic D.; Reinwald F.	Green and open space factor Vienna: a steering and evaluation tool for urban green infrastructure	2021	15	Heat wave	Well-being related to green areas	The CFV-F is calculated by dividing the weighted Green Open Space area by the total reference area (for example, the facade area, the roof area or the ground floor area). A further subdivision is made into GFF-V facade, GFF-V roof and GFF-V ground floor based on the different reference areas. Microclimate simulations and analyses were conducted using a software-based planning, optimization and certification tool called GREENPASS.	Green open space factor Vienna (GFF-V)	Vienna, Austria
							Determined through expert assessments of experts in terms of the contribution of GOS elements to social well-being and improving the quality of life of inhabitants.	Climate multiplication factor (MFI)	
							Conducted through expert assessments of experts in terms of the contribution of GOS elements to the physical, social and mental well-being of inhabitants.	Multiplication factor for biodiversity (MFIb) Wellbeing multiplication factor (MFIwb)	
50	Christina P. Wong, Bo Jiang, Ann P. Kintzig, Zhiyun Ouyang	Quantifying multiple ecosystem services for adaptive management of green infrastructure	2018	14	Flooding, heat wave	Water Storage, climate Regulation, water purification, aesthetics values	Use of the Variable Infiltration Capacity (VIC) model to simulate energy and water balances	Mean annual water volume Mean annual water area Water loss factor	Yongding River, Pechino, China
							Measurement of hourly heat index using the Beijing Meteorological Bureau's heat index equation. Measurement of hourly heat index using the Beijing Meteorological Bureau's heat index equation.	Heat index values	
							Spectrophotometric and UV analysis to measure TN and TP. Comparison of results with national water quality standards. Conducting surveys among visitors to assess preferences and perceptions of ecosystem services.	Drinking water quality Semic Value	
51	Reinwald F.; Brandenburg C.; Gabor A.; Hinterleitner P.; Kainz A.; Kraus F.; Ring Z.; Scharf B.; Titze T.	Multi-level toolset for steering urban green infrastructure to support the development of climate-proofed cities	2021	9	Heat wave	Urban heat island	COSMO-CLIM Regional Climate Model which allows simulations at a resolution of 1 km ² . (Regional Scale)	Average summer temperature Summer days (Tmax > 25°C) Tropical nights (Tmax > 30°C)	Vienna, Austria
							MUKLIMO_3 urban climate model operating at horizontal resolutions of 20-200 m from detailed data of land cover, topography, initial meteorological conditions.(Urban Scale)	Urban heat stress	
							Simulations of the MUKLIMO_3 model with changes in land cover (e.g. de-sealing, increasing the proportion of vegetation, green roofs)	Impact of climate adaptation measures	
							Using GREENPASS that combines ENVI-met and/or Rhodolic CFD simulations with practical planning to evaluate and optimize projects based on key indicators	Urban environmental impact assessment	

Figure A7. Results of applying remote sensing technologies for climate adaptation projects to address heat waves. The bibliographic references are listed in the first column and can also be found in the bibliography.

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