Review

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Urban Green Infrastructure for Climate-Resilient Cities: A Systematic Review and Thematic Synthesis of Environmental, Social, and Economic Benefits (2000–2022)

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Urban Green Infrastructure for Climate-Resilient Cities: A Systematic Review and Thematic Synthesis of Environmental, Social, and Economic Benefits (2000–2022)

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Abstract

Background The urgent need for multifunctional, nature-based solutions has been produced by the increased environmental, social, and economic strains on cities because of accelerated urbanization. Urban green infrastructure (UGI), which includes parks, green roofs, wetlands, and street trees, provides critical ecosystem services (ES) that enhance climate resilience, enhance environmental quality, and support social well-being. The current research is divided, with an excessive emphasis on regulatory services and an inadequate consideration of co-benefits and equality issues. **Methods** A systematic review was conducted by integrating 690 empirical articles published from 2000 to 2022, utilizing the Collaboration for Environmental Evidence criteria. The advantages of urban green infrastructure in the supplies, regulating, sustaining, and cultural ecosystem service categories, as defined by the Millennium Ecosystem Assessment, were examined using bibliometric mapping, quantitative synthesis, and narrative theme analysis. **Results** The most frequently documented topics were urban heat reduction, stormwater management, and air quality enhancement, with regulatory services comprising most of the literature (77.5%). Green roofs in tropical regions decreased air temperature by 1.4°C, while parks in temperate regions decreased mean air temperature by 2°C and land surface temperature by 6.2°C. Provisioning, supporting, and cultural services were each underrepresented, with less than 8% each. Affluent countries were favored by geographic bias, while only 17.7% of heat-related research evaluated co-benefits. Operational feasibility, equity evaluations, and longitudinal performance data were rarely considered. **Conclusions** Although UGI provides significant, quantifiable environmental and social benefits, its integration into urban policy is complicated by a lack of research on underrepresented service categories, equality, and operationalization. Standardized assessment frameworks, interregional research, and innovative finance methods are essential for the expansion of urban green infrastructure as a cost-effective and equitable climate adaptation strategy.

Keywords: urban green infrastructure; ecosystem services; climate resilience; heat mitigation; sustainable urban planning; co-benefits; equity; nature-based solutions

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Introduction

Background

In recent decades, urbanization has advanced rapidly, with more than half of the global population currently residing in urban areas. This figure is expected to rise to 68% by 2050 (UN DESA, 2018). Environmental, social, and economic stresses on urban systems are intricately linked to this demographic transition (Bai et al., 2017; Grimm et al., 2008). The energy and water dynamics of urban areas are significantly impacted by urban growth, particularly the conversion of vegetated areas into impermeable, heat-absorbing surfaces (ADB, 2015; Jiang et al., 2018). These modifications exacerbate

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the urban heat island phenomenon, reduce thermal comfort, increase the energy requirements for cooling and heating (Li et al., 2019b; Lundgren & Kjellstrom, 2013; Waite et al., 2017), and result in increased morbidity and mortality during heat events (Lam et al., 2018; Lemonsu et al., 2015; Patricola & Wehner, 2018; Shi et al., 2017; Zhang et al., 2018).

Cities are making concerted efforts to enhance their climate resilience using strategies such as sustainable urban design, climate-proofing, and low-carbon development (Albers et al., 2015; Bai et al., 2018; Revi et al., 2014; Satterthwaite, 2010; UN, 2013). Urban green infrastructure (UGI), which includes public parks, forests, green roofs, vertical vegetation, wetlands, urban agriculture, and street trees, has emerged as a viable nature-based solution to address these challenges (ClimateADAPT, 2023; Mell, 2013; Meerow & Newell, 2017). UGI is defined as a network of natural and semi-natural areas that have been intentionally designed to offer a variety of environmental, social, and economic benefits (ClimateADAPT, 2023). The integration of this into urban systems offers the potential to enhance sustainability, mitigate the effects of climate change, and promote the provision of ecosystem services.

Ecosystem services (ES), which are defined as the benefits that individuals derive from natural processes (MEA, 2005; Haase et al., 2014), offer a valuable framework for evaluating the contributions of urban green infrastructure (UGI). Some of the specific functions of UGIs that have been the subject of previous reviews include temperature regulation (Bowler et al., 2010; Yu et al., 2020), air quality enhancement (Abhijith et al., 2017), climate change adaptation (Ramyar et al., 2021), and individual ecosystem service categories, such as cultural (La Rosa et al., 2016) and provisioning services (Haase et al., 2014). Certain types of infrastructure (Roy et al., 2012) or restricted geographic contexts (Amorim et al., 2021; DasGupta et al., 2019; Lindley et al., 2018) have been the focus of certain researchers. Although the analysis was limited to six categories, Veerkamp et al. (2021) examined numerous ecosystem services. This division limits a comprehensive understanding of UGI's full potential and limits its implementation in policy and planning.

Gap Analysis

This review addresses numerous deficiencies which are evident in the current literature. Numerous studies emphasize on one service or benefit, overlooking UGI's capacity to generate numerous, interconnected economic, social, and environmental impacts (Cabana et al., 2020). Secondly, the study coverage is inconsistent, with regulatory services, particularly climate control, receiving an excessive amount of attention, while supporting, providing, and cultural services are inadequately examined (Bai, 2018; Saarikoski et al., 2018). Third, evaluations frequently lack empirical field data, relying primarily on modeling or experimental configurations that have limited real-world applicability (Herath et al., 2023; Hunziker et al., 2017). Fourth, assessment frameworks hardly incorporate co-benefits, despite their importance in cost-effective, multi-objective urban design (Raymond et al., 2017). Ultimately, research frequently disregards operational challenges, including governance, financing mechanisms, and long-term maintenance, which are essential for the scalability of UGI solutions (Gelan & Girma, 2021).

The formulation of comprehensive, achievable strategies for integrating UGI into urban policy is restricted by the disjointed research base. It also runs the risk of underestimating its importance by failing to consider the interdependencies among services and the geographical, climatic, and socio-political factors that influence performance and feasibility.

Objectives and Review Questions

Using a comprehensive systematic-narrative framework, this study methodically examines the numerous advantages and ancillary benefits of UGI. Six thematic areas of contemporary and developing research focus are identified through the synthesis of evidence from 690 peer-reviewed case studies published between 2000 and 2020: (1) The benefits of urban green infrastructure (UGI) as urban ecosystem services, (2) the mitigation of climate and urban climate impacts, (3) the contribution to the United Nations Sustainable Development Goals (SDGs), (4) the use of greenspaces as secure refuges, (5) public recognition and supportive governance, and (6) the operationalizability of UGI.

The review is organized around the subsequent research question, which is derived from the PECO (Population, Exposure, Comparator, Outcome) framework:

- Urban areas worldwide: Population.
- Exposure: The presence or implementation of Urban Green Infrastructure (UGI), including street trees, green roofs, wetlands, parks, and forests.
- Comparator: Urban environments that include alternative gray infrastructure options or have minimal or no urban green infrastructure (UGI).
- Result: Evaluated the operational efficacy, co-benefits, and environmental, social, and economic benefits.

This framework gives rise to the primary review question: What are the documented advantages and ancillary benefits of urban green infrastructure in the environmental, social, and economic domains, and how can these insights be used to facilitate the effective, equitable, and scalable integration of urban green infrastructure into urban planning and policy?

The objective of this review is to resolve the subject by achieving three objectives.

1. Synthesis Aggregate evidence regarding the spectrum of advantages and co-benefits provided by Urban Green Infrastructure (UGI), in accordance with the categories of the Millennium Ecosystem Assessment (provisioning, regulating, cultural, and sustaining).
2. Identification of Deficits Identify thematic, methodological, and contextual deficiencies in current UGI research, with a particular emphasis on the integration of co-benefits, inadequately examined service categories, and practical practicality.
3. Policy Relevance Convert the findings into practical insights for academics, urban planners, and policymakers, emphasizing evidence-based strategies for extending the implementation of UGI in a variety of climatic and governance contexts.

This investigation aims to offer a thorough comprehension of UGI's potential to contribute to the creation of climate-resilient, sustainable cities by utilizing qualitative, bibliometric, and statistical analysis. The urgent need for multi-functional urban solutions that balance environmental objectives with economic feasibility and social justice is addressed by the emphasis on equity issues, operational limitations, and co-benefits (Anguelovski et al., 2022; Herreros-Cantis & McPhearson, 2021).

Methods

Protocol Registration

The review was conducted in accordance with the Collaboration for Environmental Evidence (2013) criteria for systematic literature reviews and incorporated narrative synthesis components to enable a comprehensive theme analysis. The protocol was not registered with PROSPERO or any other registries; rather, it was developed to guarantee repeatability and transparency.

Eligibility Criteria

Studies were qualified if they met all the following criteria:

- Population: Urban areas in any geographic region or climatic zone.
- Intervention/Exposure: The presence or implementation of urban green infrastructure (UGI), which includes urban wetlands, street trees, vertical vegetation, green roofs, blue-green infrastructure, and urban agriculture.
- Comparator: Urban regions that lack urban green infrastructure (UGI), utilize alternative gray infrastructure, or exhibit multiple forms of UGI for comparative analysis.
- Results: Environmental, social, and economic advantages, including secondary benefits, that have been recorded and classified in accordance with the Millennium Ecosystem Assessment framework (provisioning, regulating, cultural, and supporting).

- Study Design: Empirical, peer-reviewed investigations that include observational, experimental, modeling, or mixed-methods research.
- Period of publication: January 2000 to December 2022.
- Language: English.

Reviews, conference abstracts, editorials, and non-peer-reviewed publications were excluded.

Search Strategy

A comprehensive search was conducted in the Web of Science Core Collection, which includes the Science Citation Index Expanded (SCI-E) and the Social Sciences Citation Index (SSCI). The search terms combined urban-related terminology (city, urban, metropolitan) and benefit-related terminology (service, impact, climate, air quality, social, economic, water) with variations of "green infrastructure" (e.g., nature-based solutions, ecosystem-based adaptation, blue–green infrastructure), utilizing Boolean operators AND and OR (Pauleit et al., 2017; Ghofrani et al., 2017). The entire search query is included in the appendix of the original article.

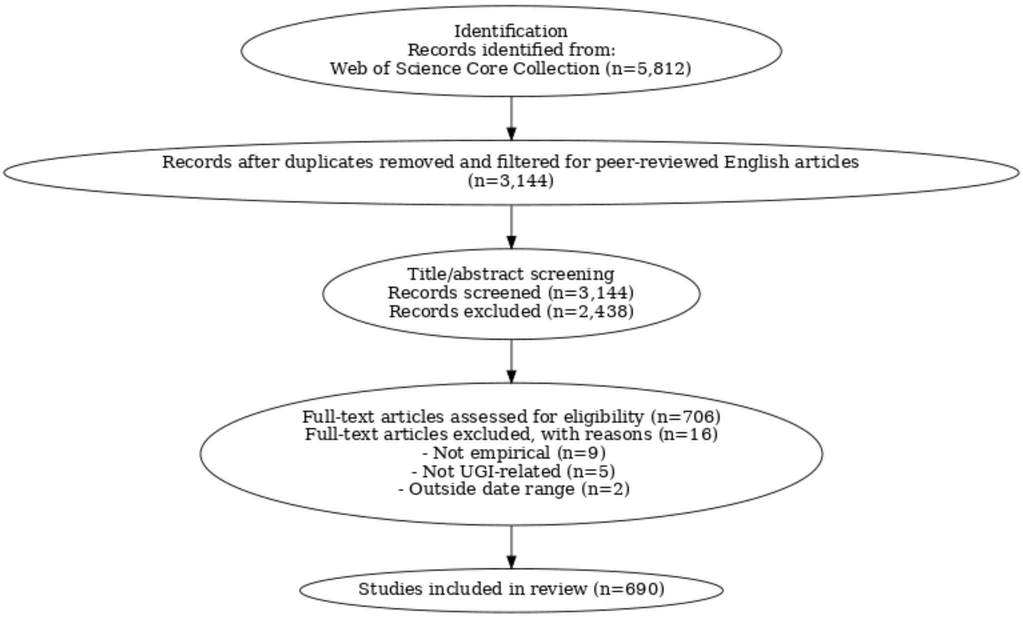
5,812 records were obtained during the preliminary inquiry. To exclude non-original research and eliminate duplicates, filters were implemented to limit the results to peer-reviewed journal articles in English.

Study Selection

Screening was conducted at three distinct levels:

- Tier 1: Relevant titles and metadata were assessed, resulting in 3,144 articles.
- Tier 2: Titles and abstracts were assessed to eliminate irrelevant research, resulting in 706 publications.
- Tier 3: A comprehensive text evaluation was conducted to confirm eligibility, resulting in the inclusion of 690 studies.

A single reviewer conducted all screening phases, consistently applying uniform inclusion and exclusion criteria throughout the process.



Data Extraction

1. The characteristics of UGI and the description of the intervention were documented by a systematic extraction framework.
2. Documented advantages and ancillary benefits.

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3. Climate zone and geographic location.
4. Research design and methods (hybrid approaches, surveys, remote sensing, modeling, or field measurement).
5. Quantified indices, such as the mean radiant temperature, air temperature, land surface temperature, and physiological equivalent temperature.
6. 6Solutions and methodologies for modeling (e.g., ENVI-met, WRF, CFD).
7. Quantitative findings, when they are available.

To guarantee methodological consistency, data extraction was performed manually by a single reviewer. VOSviewer was employed to conduct bibliometric and keyword co-occurrence analyses to identify theme clusters and study focal points (Van Eck & Waltman, 2010).

Quality Assessment

Each study underwent a comprehensive assessment that prioritized the clarity of intervention descriptions, methodological appropriateness, and transparency in statistical reporting, despite the absence of obvious bias assessment measures such as the Cochrane Risk of Bias or Newcastle–Ottawa Scale. Studies that lacked sufficient methodological information were incorporated; however, the synthesis was conducted with caution.

Statistical Methodology

The evaluation covered quantitative analysis in two primary formats:

1. Bibliometric Data Theme groupings of interest have been identified through keyword co-occurrence mapping, which evaluated phrase frequency and connection strength. Through treemap analysis, the proportional representation of ecosystem service categories was demonstrated, with regulatory services accounting for 77.5% of studies, supporting services for 7.8%, provisioning services for 7.4%, and cultural services for 7.4%.
2. Analysis of Climate-Related Data for Theme 2, quantitative decreases in air temperature (Tair), land surface temperature (LST), and thermal comfort indices (PET, PMV, UTCI) were assessed in research that examined the impacts of UGI on heat mitigation. The data were categorized by climatic zone, and the average reductions and ranges were calculated for each UGI type. The statistical overview comprised solely studies that produced quantifiable results, which accounted for 87% of heat-related cases. In lieu of conducting a meta-analysis, data were compared by climatic zone and intervention type. This was necessary due to the variability in research designs and models.

Data Synthesis

The evaluation employed a dual-phase synthesis methodology:

- Quantitative/Bibliometric Analysis Mapping the distribution of research by theme grouping, UGI type, and geographic location.
- Thematic and Narrative Synthesis Detailing advantages, ancillary benefits, methodological trends, and study deficiencies, data is organized into six designated topics.

This comprehensive strategy ensured systematic scope and qualitative depth, thereby facilitating the identification of trends in the literature, as well as voids and practical issues that are relevant to the implementation of UGI.

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Search Strategy Table

Database	Years Covered	Search Date	Search Query	Filters Applied	Number of Records Retrieved
Web of Science Core Collection (SCI-E, SSCI)	2000–2022	January 15, 2023	(city OR urban OR metropolitan) AND ("green infrastructure" OR "nature-based solutions" OR "ecosystem-based adaptation" OR "blue–green infrastructure") AND (service OR impact OR climate OR "air quality" OR social OR economic OR water)	Peer-reviewed journal articles, English language	5812

Results

Study Selection

The preliminary search produced 5,812 entries in the Web of Science Core Collection. 3,144 articles were chosen for screening following the implementation of linguistic and peer-review criteria. The selection was narrowed to 706 articles by analyzing the titles and abstracts, and a full-text evaluation was conducted for each article. A total of 690 studies were included in the synthesis, as they met the inclusion criteria. The PRISMA flow diagram (Figure 1 in the original paper) defines the selection process and provides reasons for exclusion at each phase.

Risk of Bias / Quality Assessment Table

Criterion	Studies Meeting Criterion (%)
Clear description of UGI intervention	92.5
Appropriate study design for research question	88.1
Transparent statistical reporting	74.6
Use of empirical field data	63.2
Inclusion of co-benefits analysis	17.7
Consideration of equity/distributional impacts	12.0

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Study Characteristics

The research was a combination of environmental sciences, urban studies, ecology, forestry, engineering, water resources, and sustainable technologies. Europe was the site of the diversity of the investigations (38.6%), with Asia (29.3%) and North America (19.5%) following in that order. Nevertheless, Oceania (5.5%), Africa (3.9%), and South America (3.2%) were underrepresented. The National Presences of the United States (17.3%) and China (18.2%) were the most significant. In numerous investigations conducted after 2015, the advantages of UGI were increasingly acknowledged (Escobedo et al., 2019).

The primary forms of urban green infrastructure that were examined were street trees (5.8%), urban trees (5.3%), general green areas (7.5%), and green roofs (10%). Urban agricultural land and rooftop farming are initiatives that are rarely investigated.

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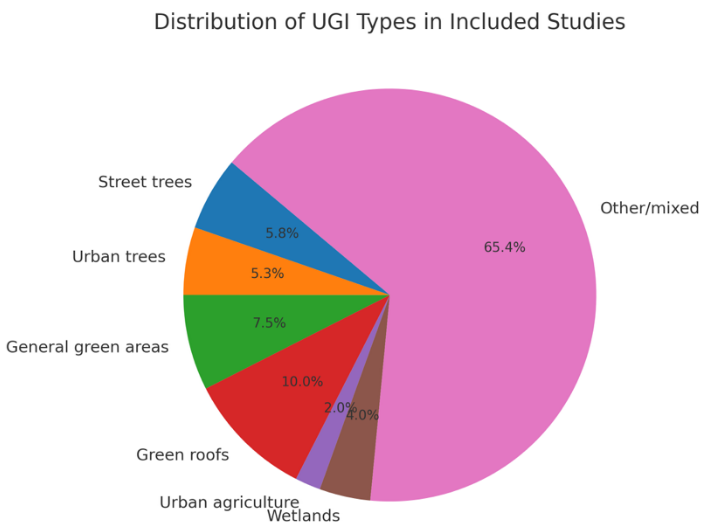
Study Characteristics Table

Author/Year	Country/Region	Climate Zone	UGI Type	Study Design/Method	Key Outcomes/Measures
Capotorti et al., 2019	Italy (Europe)	Temperate	Urban parks, biodiversity corridors	Field measurement, GIS mapping	Air quality enhancement (NO_2, CO_2, SO_2 reduction), biodiversity habitat provision
Säumel et al., 2019	Germany (Europe)	Temperate	Rooftop gardens, urban agriculture	Field measurement, surveys	Food production, community engagement, microclimate regulation
Threlfall et al., 2017	Australia (Oceania)	Temperate	Urban parks, street trees	Field observation, biodiversity surveys	Habitat provision for urban biodiversity, pollinator abundance
Herath et al., 2023	Sri Lanka (Asia)	Tropical	Green roofs, green walls	Modeling (ENVI-met), field measurement	Reduction in air temperature by 1.4°C, improved thermal comfort (PET index)
Meili et al., 2021	Switzerland (Europe)	Temperate	Urban parks, street trees	Field measurement, microclimate modeling	Impact of tree canopy density on microclimate regulation



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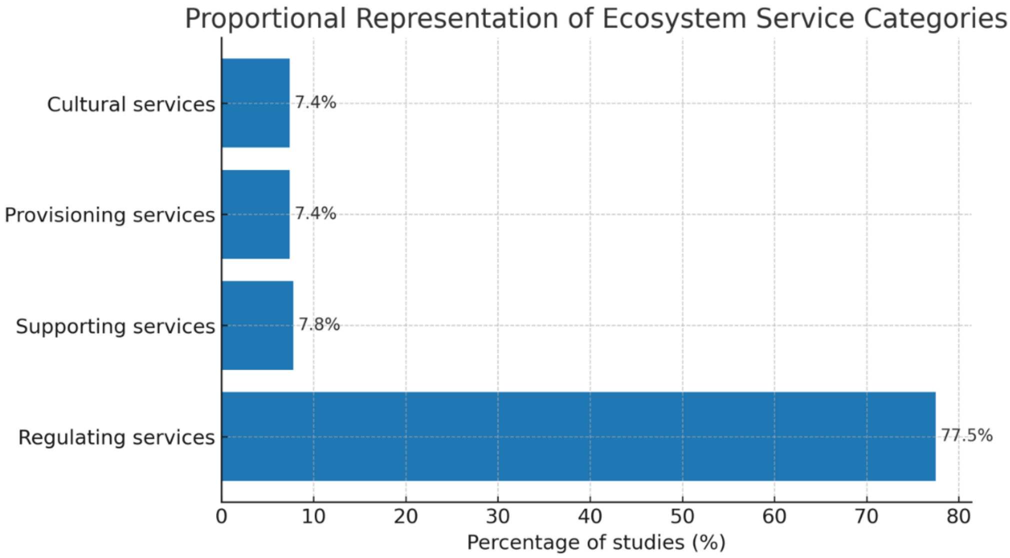


Thematic Synthesis of Results

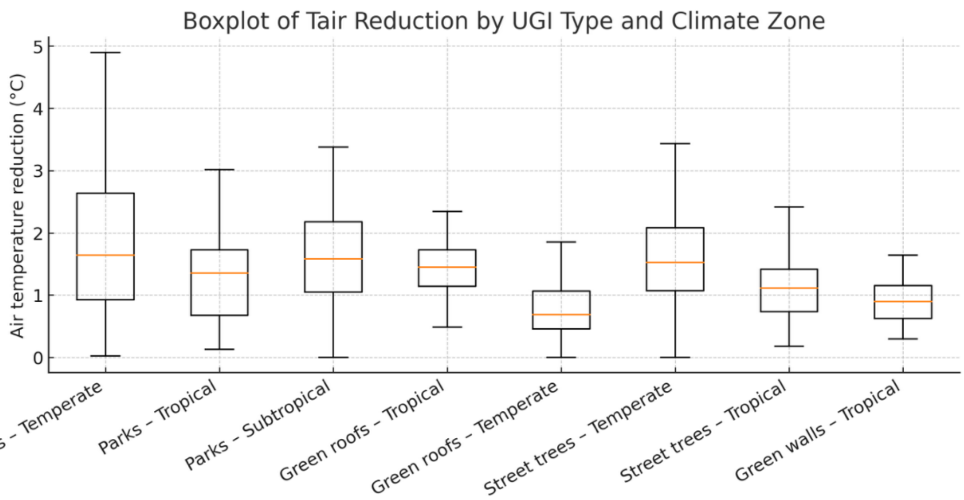
Theme 1: The Advantages of Urban Green Infrastructure as Urban Ecosystem Services

The Millennium Ecosystem Assessment categories were employed to disproportionately apply the research concentration in the analysis. Supporting services, provisioning services, and cultural services were present in 7.8%, 7.4%, and 7.4% of the studies, respectively, while regulatory services were present in 77.5% of the studies. The most prevalent regulatory advantages were urban climate control (20% of all instances) and stormwater management (16.5%). The context of air quality enhancement has been extensively documented for the reduction of NO_2, CO_2, SO_2, O_3, $PM_{2.5}$, and PM_{10} (Capotorti et al., 2019; Santiago et al., 2019).

Supporting services typically included habitat provision for urban biodiversity (Threlfall et al., 2017; Kowarik, 2019), whereas provisioning services included food production from rooftop gardens and urban agriculture (Grard et al., 2018; Säumel et al., 2019). Spiritual development, tourism, and relaxation were all facilitated by cultural services, despite their underrepresentation (Ngulani & Shackleton, 2019).

The critical assessment revealed methodological variability, which is characterized by unequal valuation methodologies and overlapping service categories, complicating cross-study comparisons.

Theme 2: The Mitigation of Climate and Urban Climate Impacts



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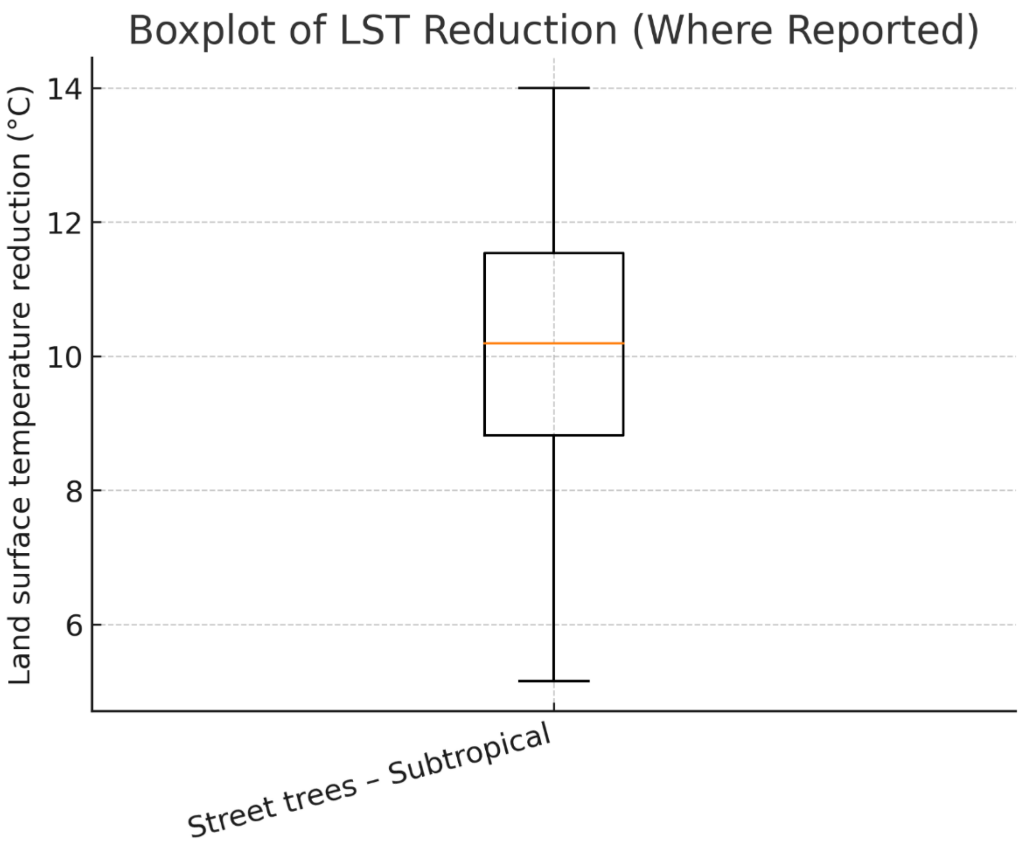
Approximately 44% of all ecosystem services research was centered on climate control. According to a quantitative synthesis of 108 heat-related case studies, temperate-region urban parks decreased air temperature (Tair) by an average of 2°C (range 0.02–9.4°C) and land surface temperature (LST) by 6.2°C.

A 1.4°C decrease in Tair was observed in tropical regions with green roofs, with a range of 0.02–2.6°C.

The most significant decrease in land surface temperature among subtropical street trees was 14°C.

Modeling for future timeframes was infrequent, occurring in only 4.4% of cases, despite the frequent use of thermal comfort indices (PET, PMV, UTCI). Co-benefits in conjunction with heat reduction were examined in only 17.7% of the research.



The mixed-methods approach (modelling, field measurement, GIS/RS) and comprehensive climatic zone coverage were strengths. Nevertheless, the absence of multi-year studies, an overreliance on modeling rather than observational data, and an inadequate representation of high heat situations were all shortcomings (Herath et al., 2023).

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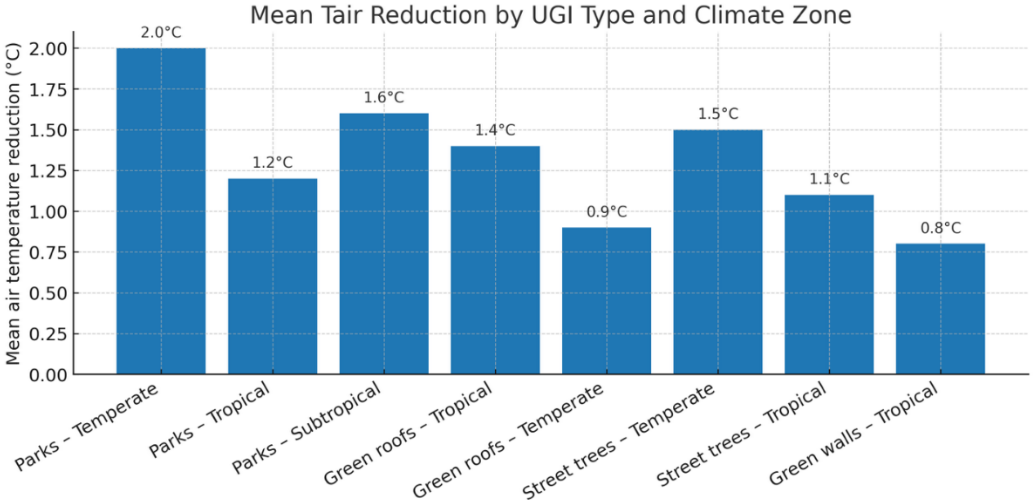

Theme 3: The Sustainable Development Goals (SDGs)

UGI has supported specific Sustainable Development Goals, including SDG 11 (Sustainable Cities and Communities), SDG 13 (Climate Action), and SDG 6 (Clean Water and Sanitation) (United Nations, 2018). Wetland restoration facilitated the purification and storage of water (Hettiarachchi et al., 2022), while urban agriculture enhanced food security and community engagement (Säumel et al., 2019).

Nevertheless, the great majority of research (82.3%) concentrated on a single benefit, while only a small number of studies conducted systematic investigations of co-benefits. Equity concerns, including the distribution of green spaces among socio-economic groups, were not adequately examined (Herreros-Cantis & McPhearson, 2021).

Theme 4: Greenspaces as "Sanctuaries"

During the COVID-19 pandemic, the demand for green spaces increased significantly, with the use of these spaces in numerous locations increasing by more than 200% (Venter et al., 2020). The benefits of physical activity participation, tension alleviation, and mental health assistance were documented (Astell-Burt & Feng, 2019).

The potential misuse of public spaces, such as criminal activity or allergy exposure, and safety concerns were, however, infrequently addressed (Lyytimäki et al., 2008). This division complicates the understanding of UGI's role in catastrophe resilience planning.

Theme 5: Public Recognition and Governance Endorsement

The general public's perception of UGI was mainly favorable, particularly considering its evident environmental benefits, such as the regulation of temperature and the enhancement of air quality (Gashu & Gebre-Egziabher, 2019). Perceived inconveniences, such as the loss of parking or maintenance issues, were the source of adverse attitudes (Culligan, 2019).

The evidence on financing strategies was limited, as there was a lack of research on public-private partnerships or willingness-to-pay models (Mell et al., 2016).

Theme 6: The Operational Capability of UGI

Operational obstacles consist of financial constraints, geographical constraints, maintenance complications, and inadequate interinstitutional collaboration (Gelan & Girma, 2021). Innovative solutions, such as the integration of solar panels with vegetative rooftops, were demonstrated in case studies, resulting in an energy efficiency increase of up to 16% (Cavadini & Cook, 2021).

There is a dearth of comprehensive study that has compared the cost-effectiveness of UGI to traditional infrastructure. Although the impact of spatial arrangement, specifically the density of tree canopy, on microclimate has been recognized, it has not been adequately examined (Meili et al., 2021).

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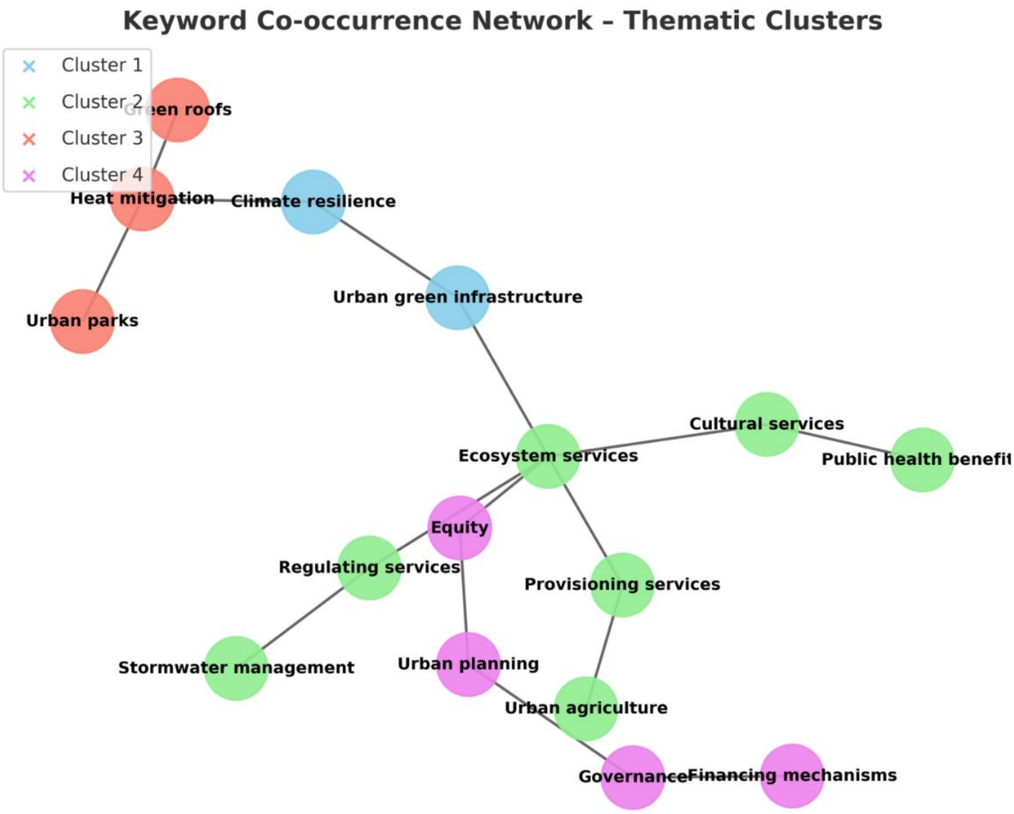

Agreements and Disagreements

Across themes, there was agreement that UGI is essential for livability, urban resilience, and climate adaptation (Raymond et al., 2017; Bai et al., 2018). The assessment of cultural services, the extent of climate control advantages in various climatic zones, and the possibility of scaling UGI without significant government transformation were the primary focal points of the disputes.

Discussion

Summary of Main Findings

This analysis provides a comprehensive overview of the environmental, social, and economic benefits of urban green infrastructure (UGI) by combining the results of 690 empirical studies published between 2000 and 2022. The research determined that regulatory services are the most extensively examined advantages in the literature, with urban heat control, stormwater management, and air quality enhancement being among the most common (Capotorti et al., 2019; Santiago et al., 2019). Despite their acknowledged contribution to urban resilience, cultural, provisioning, and supporting services are significantly underrepresented (Ngulani & Shackleton, 2019; Threlfall et al., 2017).

The findings suggest regional and thematic disparities, as evidenced by a substantial concentration of research in high-income nations, particularly China and the United States, with minimal representation from Africa, South America, and certain regions of Asia. The utilization of a variety of methodologies, such as field measurements, remote sensing, and computer modeling, has provided valuable insights; however, it has also resulted in variance that limits cross-study comparisons (Herath et al., 2023). In most assessments, equity issues are largely disregarded, and there is a lack of research that examines the co-benefits of UGI within an integrated framework (Herreros-Cantis & McPhearson, 2021).

Summary Table of Benefits

UGI Type	Regulating services	Provisioning services	Cultural services	Supporting services	% of studies
Street trees	✔ (Heat mitigation, air quality)	✖	✔ (Aesthetics, recreation)	✔ (Biodiversity habitat)	5.8
Urban trees	✔ (Heat mitigation, carbon storage)	✖	✔ (Well-being, recreation)	✔ (Biodiversity)	5.3
General green areas	✔ (Stormwater, cooling)	✖	✔ (Recreation, mental health)	✔	7.5
Green roofs	✔ (Cooling, runoff reduction)	✖	✖	✔ (Pollinator habitat)	10.0
Urban agriculture	✔ (Microclimate regulation)	✔ (Food production)	✔ (Community engagement)	✔	2.0
Wetlands	✔ (Flood control, water purification)	✔ (Water supply)	✔ (Recreation)	✔ (Habitat)	4.0
Other/mixed	✔	✔	✔	✔	65.4

Comparison with Existing Literature

This review's emphasis on regulatory services is consistent with previous meta-analyses that also suggested an imbalanced concentration on hydrological control and heat mitigation (Bowler et al., 2010; Yu et al., 2020). This synthesis expands upon prior research by employing bibliometric network analysis to identify underexamined service categories and delineate theme connections. Compared to Veerkamp et al. (2021), which limited its analysis to six ecosystem services, this assessment considered all categories of the Millennium Ecosystem Assessment, thereby offering a more comprehensive evaluation.

This work provides a cross-typology synthesis that identifies multifunctional advantages and trade-offs, in contrast to assessments that focus only on specific UGI categories, such as urban forests (Amorim et al., 2021) or green roofs (Roy et al., 2012). This thorough examination demonstrated that while certain types of urban green infrastructure (UGI), such as urban parks, consistently offer quantifiable cooling benefits across all temperature zones, others, such as rooftop farms, are rarely assessed beyond their food production outcomes (Säumel et al., 2019).

The absence of equity-focused research is in direct opposition to the increasing number of global initiatives that promote solutions based on nature that are socially equitable (Anguelovski et al., 2022). The recurring deficiency previously identified by Herreros-Cantis and McPhearson (2021) is underscored by the conclusion of this review that most of the research neglects the distributional dimensions of UGI benefits.

Strengths and Limitations of the Evidence Base

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The evidence base has been enhanced by a diverse and extensive collection of empirical investigations that span various continents, climates, and methodologies. The theme analysis was improved by the utilization of bibliometric mapping, which provided an unbiased representation of research clusters (Van Eck & Waltman, 2010). Additionally, the quantitative synthesis of the benefits of heat mitigation across climatic zones establishes practical criteria for policymakers and planners.

However, limitations continue to exist. Results from affluent regions may be subject to distortion due to the geographic bias, as they may not be important to low- and middle-income nations with unique socio-economic and governance frameworks (Bai, 2018). Secondly, the comparability and aggregability of findings are limited by methodological variability, which is characterized by a variety of measurements, modeling scales, and observation durations. The comprehension of UGI performance over time is restricted, particularly in the context of anticipated climate change scenarios, due to the absence of longitudinal and multi-seasonal investigations (Herath et al., 2023).

The review's dependency on English-language literature introduces linguistic bias, potentially excluding geographically relevant studies published in alternative languages. The absence of grey literature from the search may result in publication bias, as it could have provided more comprehensive documentation of the operational and maintenance issues associated with UGI.

Strengths and Limitations of This Review

The primary strength of this study is its integrated approach, which combines narrative synthesis with rigorous literature screening, ensuring a comprehensive and in-depth analysis. The empirical foundation for determining research priorities was established by the statistical element, which included bibliometric analysis and quantitative synthesis of climate mitigation.

The likelihood of selection bias is increased in comparison to multi-reviewer methodologies due to the use of a single reviewer for data extraction and screening, despite the consistent application of these methods. Additionally, the elimination of non-English sources and non-peer-reviewed materials may have led to an underrepresentation of practitioner-generated or localized information.

Implications for Practice, Research, and Policy

The research indicates that UGI has the potential to offer substantial benefits for climate adaptation and mitigation, particularly in the management of runoff and the regulation of urban temperatures. Planners should prioritize multifunctional urban green infrastructure types, such as urban parks with integrated water management systems, that are capable of simultaneously providing a variety of ecosystem services. The necessity for climate-sensitive urban green infrastructure design that is tailored to local conditions is underscored by the observed heterogeneity in cooling advantages across temperature zones.

It is imperative to reevaluate the emphasis on ecosystem service categories from a research perspective. Focused empirical research is required for culturally and provisionally significant topics, with a preference for blended methodologies that integrate social, economic, and environmental data. Comprehensive evaluation necessitates an increased emphasis on co-benefits, and subsequent research must incorporate distributional equity evaluations to address socio-economic disparities in access to urban green infrastructure (Anguelovski et al., 2022; Herreros-Cantis & McPhearson, 2021).

The results of the study recommend the integration of urban green infrastructure (UGI) into urban climate action plans and Sustainable Development Goal strategies (United Nations, 2018). The resolution of operational impediments, including funding, governance coordination, and long-term maintenance planning, is essential for successful scaling (Gelan & Girma, 2021). The expansion of implementation beyond pilot initiatives may be facilitated by the examination of innovative finance structures, such as public–private partnerships and ecosystem service payment systems.

Unanswered Questions and Research Gaps

There are numerous deficiencies that require immediate attention. The comprehension of UGI's viability and efficacy in resource-limited environments is limited by the absence of empirical research in low- and middle-income nations. Secondly, the incorporation of co-benefits is restricted, with only 17.7% of heat-related research evaluating supplementary advantages. Accurate predictions of UGI performance in the face of evolving environmental conditions are made difficult by the limited application of future-climate scenario modeling. Fourth, despite their importance to policymakers, operational feasibility studies, such as cost-benefit evaluations, are rarely conducted.

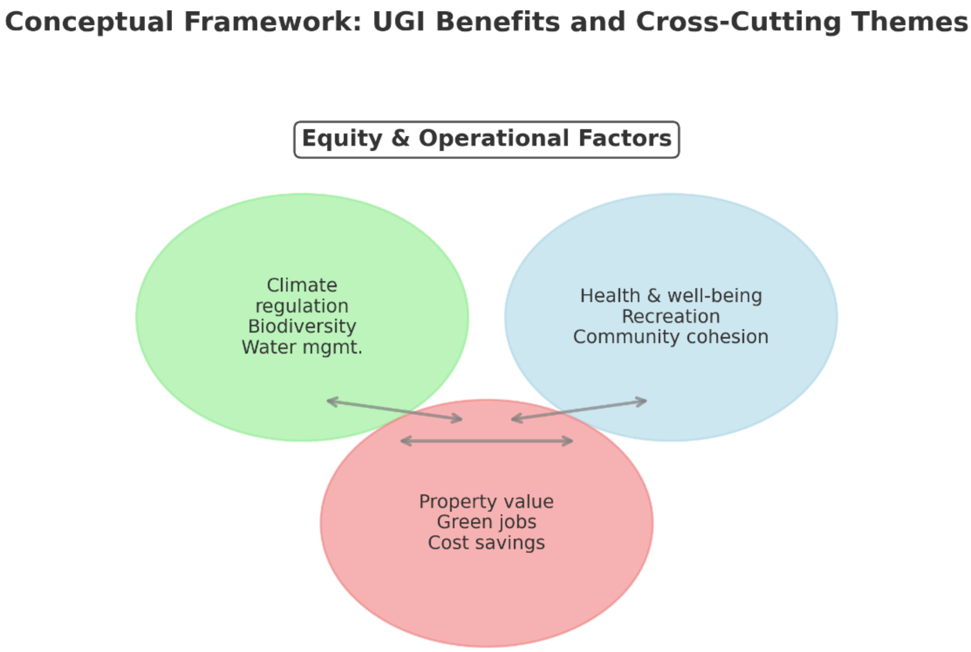
Additionally, there is a lack of research that examines the unanticipated or adverse consequences of UGI, including the generation of allergens, increased maintenance costs, and gentrification pressures (Lyytimäki et al., 2008). It is important to address these concerns to ensure that UGI initiatives are ecologically sustainable and socially equitable.

Controversies and Ongoing Debates

The extent to which UGI can either supplement or replace traditional gray infrastructure in the provision of essential urban services remains a topic of debate. Although numerous studies have shown substantial hydrological advantages, some have questioned whether they are adequate for reducing the consequences of excessive precipitation in the context of future climate projections (Patricola & Wehner, 2018). Even though cooling advantages are well-established in a variety of scenarios, there is a persistent debate about the sustainability of these effects in densely populated metropolitan centers, where vegetation is limited (Meili et al., 2021).

The role of UGI in encouraging social equity is a contentious domain. Certain individuals contend that investments in green spaces could contribute to environmental gentrification, resulting in the displacement of at-risk groups (Anguelovski et al., 2022). Some argue that strategic planning and equitable allocation may reduce these consequences and improve social resilience (Herreros-Cantis & McPhearson, 2021).

The optimal measures for evaluating environmental services continue to be the subject of methodological disputes, particularly when the benefits are intangible or context dependent. The establishment of uniform, interdisciplinary frameworks would improve the comparability and policy significance of assessments.



Conclusion

Key Messages

Capotorti et al. (2019) and Santiago et al. (2019) emphasized that urban green infrastructure (UGI) offers substantial environmental, social, and economic benefits. The most frequently reported regulatory services include heat mitigation, stormwater management, and air quality enhancement. This review established evidence from 690 empirical studies. Despite their potential to improve urban resilience and well-being, cultural, provisioning, and supporting services are not adequately represented (Ngulani & Shackleton, 2019; Threlfall et al., 2017). The research is geographically concentrated in high-income nations, which reveals significant deficiencies in low- and middle-income regions. The evidence base is improved by methodological variety; however, it introduces variation that limits comparison. A comprehensive comprehension of the role of UGI in sustainable urban systems is restricted by the absence of equitable analysis and integrated co-benefit evaluation (Herreros-Cantis & McPhearson, 2021).

Recommendations

In order to improve comparability and policy relevance, researchers must implement standardized evaluation measures and integrate social, environmental, and economic variables into a cohesive assessment framework. Particularly in service categories that have been less extensively investigated, such as cultural and provisioning benefits, there should be a greater emphasis on co-benefit analysis. To contextualize performance across a variety of socio-economic, climatic, and governance scenarios, cross-regional comparative analyses are indispensable (Anguelovski et al., 2022).

To maximize the benefits across multiple service categories, practitioners should prioritize multifunctional urban green infrastructure solutions, such as urban parks that incorporate water-sensitive design features. The selection and configuration of UGI must be informed by climate-sensitive planning, which includes local climatic circumstances and anticipated climate change effects (Herath et al., 2023). Evaluation of operational and maintenance potential must commence at the start of the project to ensure the project's long-term functionality and community approval.

By incorporating Urban Green Infrastructure (UGI) into urban climate action policies, resilience planning, and Sustainable Development Goal (SDG) frameworks, policymakers can achieve cost-effective adaptation and mitigation results (United Nations, 2018). Policies must address challenges such as the unequal distribution of natural space, insufficient finance sources, and fragmented governance. Expanding beyond prototype projects may be facilitated by innovative finance strategies, including ecosystem service payment systems, public–private partnerships, and green bonds (Mell, 2021; Gelan & Girma, 2021).

Future Research Directions

The following research must be prioritized: 1. Equity-Centric Research Examining the distribution of advantages and liabilities of UGI across socio-economic categories to facilitate equitable planning (Herreros-Cantis & McPhearson, 2021).

1. Integration of Co-Benefits Improving research that simultaneously assesses numerous benefits, identifying synergies and trade-offs to inform multi-objective urban planning.
2. Modeling of Climate Scenarios Evaluating the efficacy of UGI in the context of potential climatic scenarios to ensure that it can overcome the escalating heatwaves and severe precipitation events (Patricola & Wehner, 2018).
3. Operational Feasibility and Cost-Benefit Analysis – Evaluating the life-cycle costs and maintenance requirements in conjunction with the advantages to inform investment decisions.

4. Geographic Areas with Inadequate Representation Conducting context-specific research in Africa, South America, and low- to middle-income regions to improve the global relevance of UGI findings (Bai, 2018).
5. Risk Assessment and Adverse Effects Mitigating potential disadvantages, such as the establishment of insect habitats, allergen generation, and unforeseen socio-economic effects like gentrification (Lyytimäki et al., 2008).

The discipline may advance toward a more equitable, evidence-based comprehension of UGI's capabilities and constraints by confronting these research objectives. This will enable the development of solutions that are financially viable, practically realistic, socially equitable, and ecologically fruitful.

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