https://doi.org/10.4467/21995923GP.25.006.22861 GEOINFORMATICA POLONICA
24: 2025

Akim Oladokoun[1]
https://orcid.org/0009-0005-4536-1904
Fousseni Folega[2]
https://orcid.org/0000-0001-9097-3524
Bertrand Nero[3]
https://orcid.org/0000-0003-1598-851X
Djibril Konate[4]
https://orcid.org/0000-0001-5441-8558
Madjouma Kanda[5]
https://orcid.org/0009-0003-4605-8750
Kperkouma Wala[6]
https://orcid.org/0000-0002-7533-6356
Komlan Batawila[7]
https://orcid.org/0000-0003-2781-3063

URBAN BIODIVERSITY, ECOSYSTEM SERVICES AND THE EFFECTS OF CLIMATE CHANGE IN URBAN ENVIRONMENTS: A BIBLIOMETRIC REVIEW

[1] Geomatics and Ecosystem Modeling, Laboratory of Botany and Plant Ecology (LBEV), Department of Botany, Faculty of Sciences, University of Lome, Lomé, Togo
oladokoun@gmail.com
[2] Geomatics and Ecosystem Modeling, Laboratory of Botany and Plant Ecology (LBEV), Department of Botany, Faculty of Sciences, University of Lome, Lomé, Togo
ffolegamez@gmail.com
[3] Department of Forest Resources Technology, FRNR, Kwame Nkrumah University of Science and Technology, PMB, Kumasi, Ghana
nerbefest@yahoo.com
[4] Geography Department, Péléforo Gon Coulibaly Korhogo University, Ivory Coast
konatedjibson@yahoo.fr
[5] Geomatics and Ecosystem Modeling, Laboratory of Botany and Plant Ecology (LBEV), Department of Botany, Faculty of Sciences, University of Lome, Lomé, Togo
kmadjouma@gmail.com
[6] Geomatics and Ecosystem Modeling, Laboratory of Botany and Plant Ecology (LBEV), Department of Botany, Faculty of Sciences, University of Lome, Lomé, Togo
kperkouma.wala@gmail.com
[7] Geomatics and Ecosystem Modeling, Laboratory of Botany and Plant Ecology (LBEV), Department of Botany, Faculty of Sciences, University of Lome, Lomé, Togo
batawilakomlan@gmail.com

Abstract

Urban biodiversity, although often underestimated, plays a key role in providing vital ecosystem services such as climate regulation, air purification and others. However, anthropogenic pressures, including rapid urbanization and land use changes, exacerbate the effects of climate change, and seriously threaten these services. This bibliometric review aims to analyze research

conducted between 1990 and 2024 on urban biodiversity assessment and management, ecosystem services, and the impacts of climate change. The Publish or Perish 8 (PoPe) software is used because of its information and its flexibility of use for the different analyses, which are processed with the Excel 2013 software. Out of 1,644 publications with PoPe, 345 are select after clearance and subsequently analyze. The year 2017 marks the most prolific year of publication of articles for the mixing of concepts: "biodiversity", "ecosystem services", "urban dynamics" and "climate change". From 1990 to 1996, we noted a low rate of articles according to these concepts throughout the world and it was in 2019 and 2020 that scientific research gained momentum in the Asian continent (128 publications) and more precisely in China (22.33 %) and India (7.86 %). Through these publications (articles, books, conferences and others), the publisher having been cited the most is Elsevier (17,359 citations). From the sampled publications, researchers in the assessment and management of biodiversity (33.41 %), the mapping and modeling of ecosystem services (27.27 %) as well as the dynamics of land use in urban areas (21.13 %) and the impacts of climate change (18.19 %) used various methods. These different methodological approaches were chosen based on the objective and year of the research, the availability of resources and the reliability of the results. This review has a capital importance in the sense that it provides a range of information regarding urban ecology.

Keywords: urban biodiversity, bibliometric review, ecosystem services, dynamics, Togo

BIORÓŻNORODNOŚĆ MIEJSKA, USŁUGI EKOSYSTEMÓW I SKUTKI ZMIAN KLIMATU W ŚRODOWISKACH MIEJSKICH: PRZEGLĄD BIBLIOMETRYCZNY

Abstrakt

Miejska różnorodność biologiczna, choć często niedoceniana, odgrywa kluczową rolę w zapewnianiu istotnych usług ekosystemowych, takich jak regulacja klimatu, oczyszczanie powietrza i inne. Jednak presja antropogeniczna, w tym szybka urbanizacja i zmiany użytkowania gruntów, nasilają skutki zmian klimatu i poważnie zagrażają tym usługom. Niniejszy przegląd bibliometryczny ma na celu analizę badań przeprowadzonych w latach 1990–2024 w zakresie oceny i zarządzania różnorodnością biologiczną w miastach, usług ekosystemowych oraz wpływu zmian klimatu. Oprogramowanie Publish or Perish 8 (PoPe) zostało wykorzystane ze względu na swoje możliwości analityczne i elastyczność, a dane przetwarzano przy użyciu programu Excel 2013. Spośród 1644 publikacji z PoPe, 345 zostało wybranych po sprawdzeniu, a następnie poddanych dalszej analizie. Rok 2017 okazał się najbardziej obfity pod względem publikacji artykułów dotyczących mieszania pojęć: „różnorodność biologiczna", „usługi ekosystemowe", „dynamika miejska" i „zmiany klimatu". W latach 1990–1996 odnotowano niski wskaźnik artykułów dotyczących tych zagadnień na całym świecie, a dopiero w 2019 i 2020 r. badania naukowe nabrały tempa na kontynencie azjatyckim (128 publikacji), szczególnie w Chinach (22,33 %) i Indiach (7,86 %). Wśród tych publikacji (artykuły, książki, konferencje i inne) najczęściej cytowanym wydawcą był Elsevier (17 359 cytowań). Spośród wybranych publikacji badacze zajmujący się oceną i zarządzaniem różnorodnością biologiczną (33,41 %), mapowaniem i modelowaniem usług ekosystemowych (27,27 %), a także dynamiką użytkowania gruntów na obszarach miejskich (21,13 %) oraz wpływem zmian klimatu (18,19 %) stosowali różnorodne metody. Te różne podejścia metodologiczne zostały wybrane w zależności od celu i roku badań, dostępności zasobów i wiarygodności wyników. Niniejszy przegląd ma istotne znaczenie, dostarczając cennych informacji dotyczących ekologii miejskiej.

Słowa kluczowe: różnorodność miejska, przegląd bibliometryczny, usługi ekosystemów, dynamika, Togo

1. INTRODUCTION

Biodiversity and ecosystem services play a crucial role in maintaining the health and well-being of urban populations [1, 2]. Urban ecosystems, although often perceived as environments dominated by human activity, support a significant diversity of flora and fauna that contribute to a multitude of ecosystem services [3, 4]. These services, ranging from climate regulation to water purification [5], are essential for the resilience and sustainability of cities in the face of the growing challenges posed by climate change [6, 7]. However, uncontrolled urbanization and land use changes place considerable pressure on these natural systems, altering their capacity to provide vital services [8].

Indeed, urban dynamics have profoundly transformed natural landscapes, leading to fragmentation of habitats and a loss of biodiversity [9]. These chang-

es have direct impacts on ecosystem services, such as temperature regulation, air and water quality, and natural hazard management [10, 11]. Furthermore, climate change amplifies these impacts by altering temperature and precipitation regimes, thereby influencing the distribution and functioning of urban species [12]. It is therefore essential to fully understand the links between biodiversity, ecosystem services and climate change for the implementation of adaptation and impact reduction strategies that are truly effective in urban areas following research. A key driver of innovation and economic development is scientific research. Thus, understanding the dynamics of production and dissemination of scientific knowledge is crucial for decision-makers, researchers and academic institutions [13, 14]. In this regard, bibliometric studies provide valuable tools to evaluate and analyze research trends and impact [15, 16]. Bibliometric is defined as the discipline that applies quantitative methods to the study of scientific publications allowing the measurement of various aspects of scientific production, such as the number of publications, citations, co-author networks and institutional collaborations [17–19]. By analyzing publication trends, collaborative networks, and emerging research themes, these studies help identify research gaps and future priorities [20]. With the exponential increase in scientific publications over the past decades, it is essential to have up-to-date analyzes to identify recent developments and future research directions. In addition, it offers a synthetic and critical vision of the current state of research providing valuable information for researchers and decision-makers [21, 22].

The objective of this article is to bring together knowledge from research about assessment of urban biodiversity, ecosystem services and effects of climate change in urban environments. More specifically, the research method used in this specific case is the bibliometric analysis of the work carried out on assessment methods and management strategies for species and ecosystem diversity, as well as on the ecosystem services provided by urban biodiversity and the impacts of climate change in urban areas. In addition, the temporal trends in the number of articles published, number of citations, on this subject matter, the regional distribution, the most influential researchers and publishing house have been determined or outlined. In order to better carry out this review, several research questions were asked, as follows:

1) What are the temporal and spatial trends in publications on urban biodiversity, dynamics and Ecosystem services?
2) Which methods dominate the assessment and management of urban biodiversity?
3) What techniques are prevalent in evaluating, mapping, and modeling urban Ecosystem Services?
4) How has research on climate change impacts in urban areas evolved?

2. MATERIALS AND METHODS

This bibliometric review is based on scientific articles published between 1990 and 2024 with keywords such as “biodiversity”, “ecosystem services”, “urban dynamics” and “climate change”. To make this research more relevant, a methodology of three (03) steps is adopted. The first step is to make combinations between the keywords using “and” with “or”. Thus, the results were obtained through the software Publish or Perish 8 (PoPe) whose search engines used are Google scholar (), Semantic scholar () and Crossref (). This application has the facility to provide information on the number of citations, the author(s), the year of publication, the source, the publisher, etc., the summary of the article [23]. In the second step, it is a matter of combining the research results generated by PoPe (a total of 1644 publications) in an Excel sheet while taking care to eliminate duplicates of articles, books, conferences... and purify the data (a total of 345 publications are obtained). These are filtered according to their link with the keywords and according to their degree of relevance (number of citations, original value, quality of production, etc.). In the third step, the statistical software Excel 2013 is used to record the data from the selected articles. In particular, articles relevant to the research objectives and methodologies employed were extracted to conduct a spatio-temporal trend analysis of the publications, assess the limitations of the methods used, and highlight advancements in the field of urban ecology (Fig. 1).

3. RESULTS AND DISCUSSIONS

3.1. Spatio-temporal analysis

The number of publications in relation to the year of publication shows that the highest number of articles published is observed in 2017 (n=176) (Fig. 2).

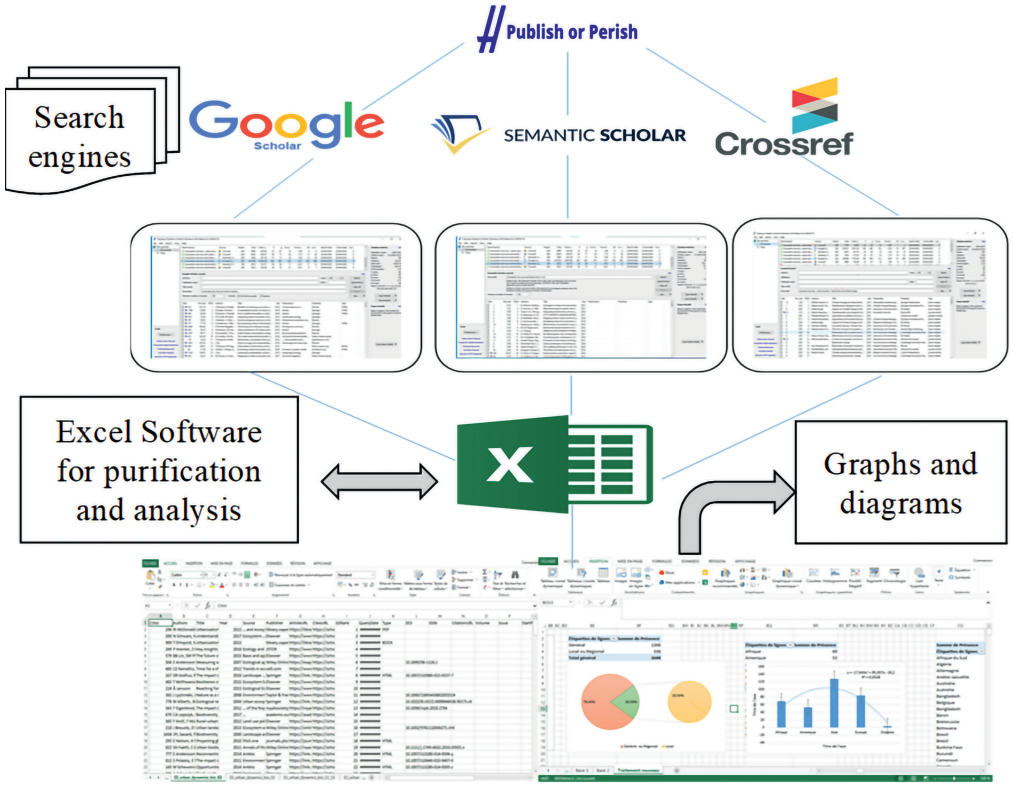

Fig. 1. Methodology chart showing analysis steps
Ryc. 1. Schemat metodologii przedstawiający etapy analizy

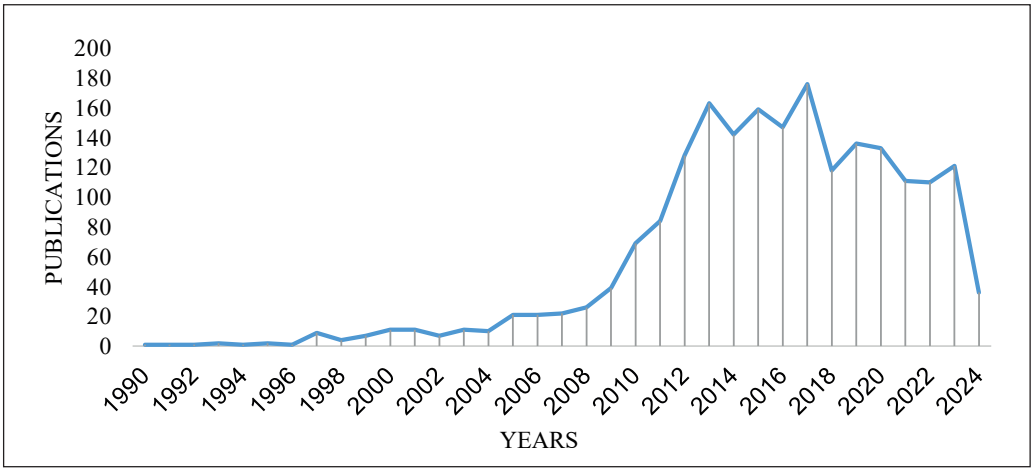

Fig. 2. Distribution of the number of publications by year
Ryc. 2. Rozkład liczby publikacji w poszczególnych latach

The year 2013 (n=167) marks the second year with the most publication of articles referring to the key words ("biodiversity", "ecosystem services", "urban dynamics" and "climate change"); showing then the value of urban ecology.

Concomitantly, the number of authors who published in 2017 (527 authors) was greater than in 2013 (425 authors) and are the highest. The lowest number of articles and authors were observed in years 1991, 1992 and 1995 (one article and one author).

Overall, between 1990 and 1996 on the five (05) continents (Africa, America, Asia, Europe and Oceania), the low number of publications relating to the different concepts is not significant (Fig. 4). In addition, the publication of articles, books, etc. of studies carried out in Asian countries progressed over time with peak number of published articles on these concepts recorded in 2019 and 2020. This is the result of favorable government policies, massive investments in research and development (China spent approximately 2.23 % of its GDP in 2019, compared to 1.5 % in 2000 [24]), the expansion of higher education, a large young population, technological innovation and international collaboration [25, 26]. These factors combine to create an environment conducive to abundant and high-quality scientific production. In Europe, the flow of publications is more noted between 2014 and 2016; for Africa, these publications cover the period 2014–2023. Researchers from the American continent formed by South America and North America countries carried out more research addressing the concepts of this journal in 2014. The rate of articles in Oceania compared to this research over the period 1990–2024 is very low (Fig. 3).

According to Fig. 4, the majority of cited publications were published by Elsevier (17,358 citations) followed by the Wiley Online Library (5,120 citations). Publishers like Wiley Online Library (5,120 citations), journals.sagepub.com (4,201 citations), books.google.com (2,036 citations), and JSTOR (1,683 citations) have publications that have been cited by multiple researchers. This is because it is the result of a combination of very rigorous scientific quality, the value of the journals, wide dissemination, effective promotion strategies, and technological innovation. These elements combine to make published research more visible, influential and recognized.

The majority of publications (79.44 %) is a general or regional manner because it relates on the one hand to a continent or to a group of countries on a continent and on the other hand to only one country. Roughly, 20.56 % of publications come from studies carried out in cities, towns, provinces, regions, etc. of a country (Fig. 5). These different publications linked to this bibliometric review work are unevenly distributed around the world. Articles, books, etc. from the Asian continent occupy a significant portion (128); then comes Europe and Africa with 84 and 69 publications respectively and finally Oceania with 4 publications relating to work (Fig. 6). Subsequently, studies carried out in China (22.33 %), India (7.86 %) and the United States (7.86 %) are the most represented. Those of the first two (02) countries cited above (China and India) represent a high rate for Asian countries; then in France and Spain for Europe and finally those of South Africa, Ethiopia, and Senegal for Africa.

In Togo, publications addressing the different concepts exist but considering those combined in this review, they are largely weak, hence the need for a long and broad exploration for better sustainable cities on a national level.

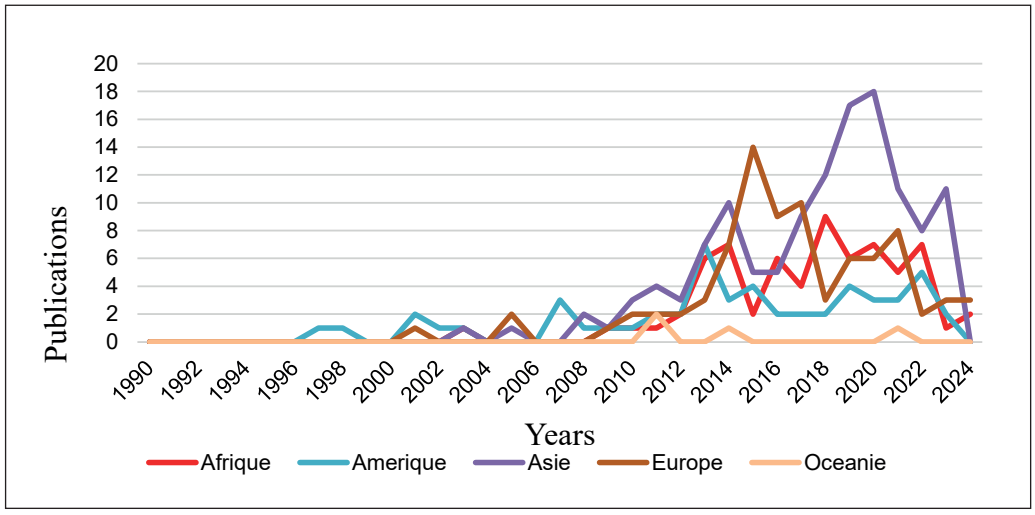

Fig. 3. Evolution of publications according to continent and by year
Ryc. 3. Ewolucja publikacji według kontynentu i roku

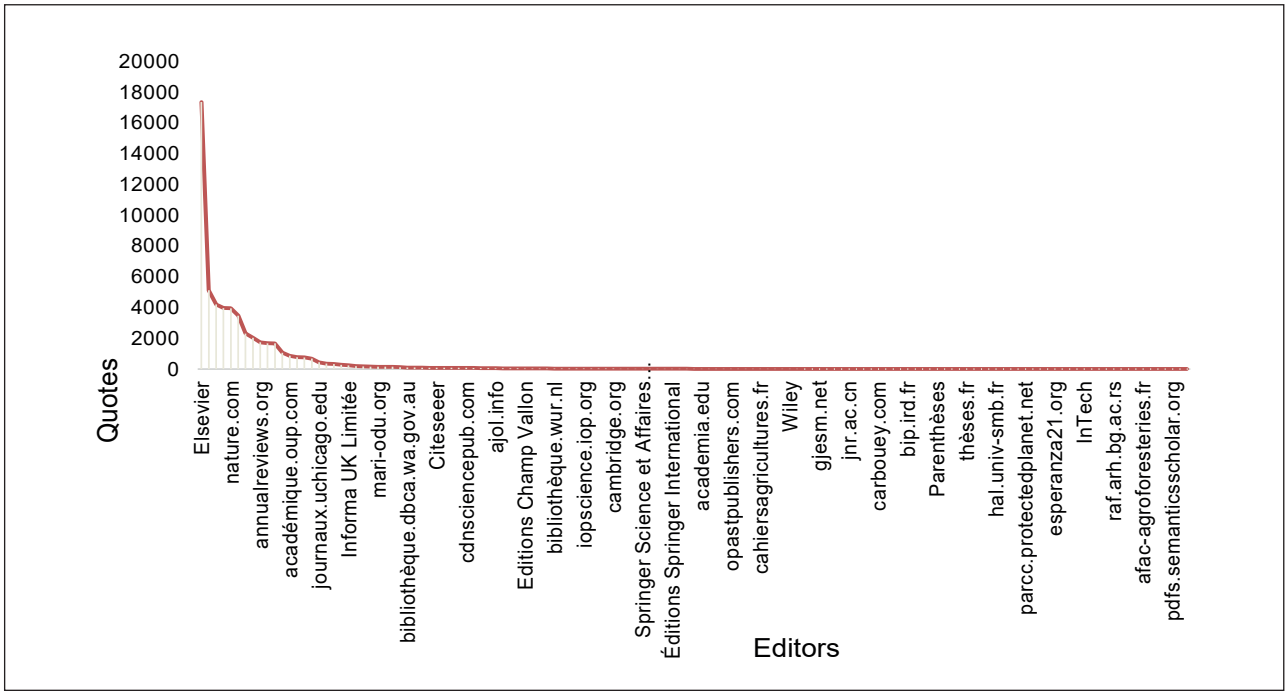

Fig. 4. Distribution of citations by publishing house
Ryc. 4. Rozkład cytowań według wydawnictwa

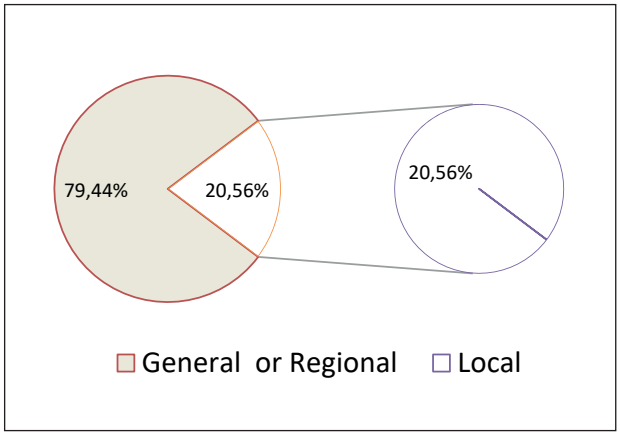

Fig. 5. Scope of publications
Ryc. 5. Zakres publikacji

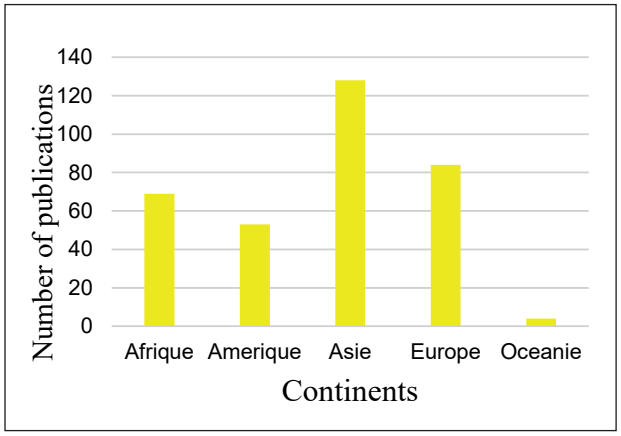

Fig. 5. Scope of publications
Ryc. 5. Zakres publikacji

3.2. Thematic analysis according to review

From the analysis of the various publications following a rigorous reading, it emerges the dispatching in four (04) different themes including: assessment and management of urban biodiversity (33.41 %); evaluation, mapping and modeling of ecosystem services (27.27 %); landuse dynamics in urban areas (21.13 %) and climate changes in urban areas effects (18.19 %).

3.2.1. Assessment and management of urban biodiversity

Assessing urban biodiversity relies on a wide range of methodological approaches, from direct field observations to advanced spatial analyses and integrated modeling frameworks. The following table (Table 1) summarizes the main categories of methods used in the literature, along with their purposes and key references.

It highlights the dominance of field-based assessments, complemented by remote sensing and GIS techniques, as well as various biodiversity indices and models that help evaluate ecological dynamics, habitat quality, and human impacts within urban environments.

From all publications, 147 addressed urban biodiversity and the systematic analysis identified three (03) main assessments method (Table 1) such as field–based assessments; remote sensing and GIS; biodiversity indices and models.

For the first assessment method, it provides essential baseline data required for further analytical, modeling, and comparative approaches. The second one allows large-scale assessment without extensive ground

Table 1. Methods for assessing and managing urban biodiversity
Tabela 1. Metody oceny i zarządzania różnorodnością biologiczną obszarów miejskich

Categories	Methods, Indices or Models	Descriptions	References
Field-Based Assessments (65.31%, n=96)	Itinerant survey	Used to identify plant species in urban environments through species listing and collection of abundance and distribution data.	[27–29]
	Dendrometric measurements (DBH > 10 cm)	Measurement of tree diameter at breast height and geographic parameters to assess forest structure, health, and spatial distribution.	[28, 30]
	Diversity indices and phytogeographic/ biological type classification	Field data used to compute diversity indices and classify species by biological forms and phytogeographic affinity.	[28, 30]
	Inventory of exotic species	Identification of exotic plants in urban green spaces to assess naturalization risks and ecological impacts.	[31]
Remote Sensing and GIS (25.85%, n=38)	Remote sensing and the City Biodiversity Index (CBI)	Integration of satellite imagery and spatial datasets with the CBI to assess 23 indicators grouped into biological diversity, ecosystem services, and governance/management.	[32]
	Spatial mapping and monitoring	Enables mapping of biodiversity patterns, detecting changes over time, and identifying priority conservation areas.	[32]
Biodiversity Indices and Models (8.84%, n=13)	Biodiversity scenarios	Projection of future biodiversity changes based on climate change, land-use/land-cover changes, or combined scenarios.	[33]
	GLOBIO 3	Model estimating short- and medium-term biodiversity change using mean species abundance relative to undisturbed ecosystems.	[34]
	Natural Capital Index (NCI)	Quantifies biodiversity richness and ecosystem service provision of natural ecosystems.	[35]
	Biological Integrity Index (BII – Southern Africa)	Assesses drivers affecting biodiversity using criteria from the Convention on Biological Diversity.	[36]
	Nature Index (NI – Norway)	Integrates ecological characteristics, conservation data, and expert knowledge into a set of biodiversity indicators; used as a policy-support tool.	[37]
	Environmental Sustainable Cities Index (ESCI – Korea)	Adapts GCI, EPI, and CBI frameworks; uses 20 indicators across four categories (indigenous biodiversity, living environment, ecosystem services and governance).	[38]
	City Biodiversity Index (CBI / Singapore Index)	Adopted at CBD COP-9 (2008); applied in Japan, India, Sri Lanka, Moscow, and elsewhere to evaluate urban biodiversity and conservation efforts.	[39–43]

surveys; complements field-based methods. For the last one, it provides standardized tools for biodiversity evaluation, comparison, and policy development, though still limited by data availability and integration into planning.

All these indices and models collectively enable standardized evaluation, projection, and management of urban biodiversity, facilitating comparisons and policy development across diverse regions. Field methods remain prevalent due to their precision, but remote sensing is rising for cost-effectiveness. For CBI index, it is underutilized due to data sources available, while management strategies need better integration with urban planning to overcome governance barriers.

3.2.2. Evaluation, mapping and modeling of ES

Evaluating ecosystem services in urban environments requires a combination of biophysical, economic, socio-ecological, and modelling approaches. Table 2

Table 2. Ecosystem service assessment methods and models
Tabela 2. Metody i modele oceny usług ekosystemowych

Categories	Methods or Tools	Descriptions	References
Biophysical Assessments (40%, n=48)	MEA & TEEB classification	Ecosystem services categorized as provisioning, regulating, cultural, and supporting, adapted to urban environments.	[44, 45]
	Biophysical ecosystem service assessment	Uses ecological and natural science methods to describe ecological conditions, environmental change, and consequences of management.	[46, 47]
	Biomass estimation using remote sensing	GEDI LiDAR + optical remote sensing to estimate aboveground biomass and carbon storage.	[48]
	Global/continental ES supply mapping	Mapping ES supply at global and continental scales to evaluate spatial distribution.	[49, 50]
	Multi-scale ES mapping	Uses remote sensing and spatial associations to map ES at multiple scales.	[51]
	Landscape connectivity tools	Use of PANDORA 3.0 (QGIS plugin) for urban ecological connectivity planning.	[52]
Economic Valuation (30.83%, n=37)	Payments for ecosystem services (PES)	Assigns monetary values to ES; considers PES as a key innovation in biodiversity conservation.	[53, 54]
	Contingent valuation	Surveys assessing willingness to pay (WTP) or willingness to accept (WTA) for changes in ES, particularly cultural and supporting services.	[55– 57]
	Replacement cost valuation	Economic valuation by calculating the cost of replacing natural ES with human-made alternatives.	[58]
	Integrated ecological--economic frameworks	Combines ecological conditions and economic metrics for monetary valuation of ES.	[59, 60]
Socio-Ecological Methods (16.67%, n=23)	Surveys & interviews	Used to capture local perceptions and contextual knowledge of ES. Includes ethnobotanical approaches and expert consultation.	[61–65]
	Participatory mapping	Engages communities to map cultural ES and understand local values.	[66]
	Socio-ecological ES mapping	Mapping ES supply and demand using socio-ecological indicators (Vacant land in NYC).	[67, 68]
	Data extrapolation	Uses primary data extrapolated to entire study areas for ES valuation.	[69]

Categories	Methods or Tools	Descriptions	References
Integrated ES Modelling (10%, n=12)	InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs)	Widely used flexible tool quantifying natural capital, modelling trade-offs, and supporting conservation and development decisions.	[71, 72]
	OLS regression	Non-spatial regression identifying global associations between drivers and ES; provides statistical screening of significant factors.	[73, 74]
Quantitative Models for ES Assessment	IUEMS platform (China)	Online ES modelling platform (climate regulation, carbon sequestration, recreation) using 30 m resolution grids; accessibility restricted to Chinese users.	[75, 79]
	GWR (Geographically Weighted Regression)	Spatial regression modelling local variations and spatial heterogeneity; useful for planning and policy applications.	[77, 78]
	Location entropy	Measures ES distribution and abundance at grid scale; evaluates local ES concentration.	[75]
	Gini coefficient	Measures spatial equity in ES distribution across concentric zones in cities.	[75, 76]

provides an overview of the main methods and tools used in the literature, detailing their functions and corresponding references. The strong representation of biophysical assessments, followed by economic valuation techniques and socio-ecological methods, is highlighted. All of this underscores the growing role of integrated ecosystem service models and advanced quantitative tools for spatial analysis and decision support in future urban planning.

In this analysis, 120 publications (26.84 %) focused on ES is categorized in different group (Table 2) such as biophysical assessments, economic valuation and integrated modeling.

Ecosystem services derived from biodiversity constitute essential components of ecological functioning and human well-being, and they provide a robust basis for communicating the significance of nature to a wide range of stakeholders. Biophysical assessment methods supply the foundational ecological information required for the quantification, spatial characterization, and modelling of ecosystem services. These approaches are complemented by socio-ecological methods, which capture perceptual, cultural, and contextual dimensions and thereby enhance the comprehensiveness of ecosystem service valuation.

Economic valuation techniques further extend this analytical framework by assigning monetary values to ecosystem services, highlighting their direct and indirect benefits, and reinforcing the critical role of biodiversity conservation in policy formulation and sustainable development planning.

Modelling tools also play a central role in ecosystem service assessment. InVEST model offers a coherent family of models that quantify natural capital in a transparent and operational manner, enabling decision-makers to evaluate trade-offs among alternative land-use scenarios and integrate conservation principles into development strategies. The IUEMS platform provides additional modelling capacities focused on climate regulation, carbon sequestration, and recreational services at fine spatial resolution. Ensuring the robustness of outputs from these tools requires the use of complementary indicators such as location entropy and the Gini coefficient, which characterize the spatial distribution and equity of ecosystem services [75]. However, access to IUEMS remains restricted, as registration is limited to users operating within Chinese territory.

3.2.3. Land use dynamics in urban areas

Understanding landuse and landcover dynamics requires a wide array of analytical tools that capture how cities expand, transform, and reorganize over time. This table brings together the major approaches used in contemporary LULC research, ranging from classical remote-sensing techniques to advanced modelling frameworks. It also outlines the data sources, indices, and spatial metrics commonly applied to monitor ur-

ban change, as well as the simulation models used to predict future growth patterns (Table 3). Collectively, these methods form a comprehensive toolkit for examining urbanization processes, assessing landscape transformations, and supporting evidence-based planning in rapidly evolving urban environments.

This section examines research based on land use dynamics in urban areas with all methods commonly used. Thus, 93 publications representing approximately 27.27 % of the total dataset were obtained (Table 3).

Urban dynamic models play a crucial role in simulating both current and future patterns of urban development, thereby providing essential support for sustainable planning initiatives [125]. The selection of satellite imagery for such analyses (Landsat, Sentinel, SPOT, or other multispectral datasets) depends on the research period, specific objectives, and data accessibility. In this context, modelling has become a central component of urban ecology, enabling the exploration of spatial transformations and long-term development trajectories.

Several urban growth models that are freely accessible or publicly available have been widely adopted in scientific research. These include agent-based simulation models (ABMs) such as UrbanSim (Urban Simulation), OBEUS (Object-Based Environmental Urban Simulation); cellular automata (CA) models such as SLEUTH (Slope, Land cover, Exclusion, Urbanization, Transportation, and Hillshade), CLUE (Conver-

Table 3. Land-use dynamics assessment methods in urban areas
Tabela 3. Metody oceny dynamiki użytkowania gruntów na obszarach miejskich

Categories	Methods or Tools or Data	Descriptions	References
General Scope of Land-Use Dynamics Research	Urban land-use and land-cover change (LULC) analysis	Study of how urban land is developed, transformed, or redeveloped (residential, industrial, commercial, green spaces). Influenced by demographic growth, planning policies, economic development, technology, and environmental factors.	[80, 89]
	Spatio-temporal landscape variation	Identification of landscape units, temporal changes, and spatial dynamics to understand urban growth.	[90]
Remote Sensing for LULC Change	Aerial photographs and high-resolution imagery	Used for detailed land-use classification and detecting fine-scale changes.	[91, 92]
	SPOT images	Medium-resolution imagery used to monitor vegetation and urban expansion.	[93]
	DMSP-OLS nighttime lights	Detects urban expansion through luminosity patterns; useful for economic activity proxies.	[94]
	ASTER images	Applied for land-surface temperature, geology, and land-cover mapping.	[95–97]
	Sentinel images	Widely used for vegetation, built-up area detection, and spatio-temporal LULC monitoring.	[98, 99]
	Landsat images	Long-term monitoring of urbanization and land-cover transitions; most common dataset used.	[85, 100, 101]
Remote Sensing Indices for Urban Analysis	NDVI (Normalized Difference Vegetation Index)	Quantifies vegetation abundance and health.	[102, 104]
	NDBI (Normalized Difference Built-up Index)	Detects built-up areas.	[105]
	UI (Urban Index)	Identifies urban surfaces using multispectral data.	[106]
	NDBaI (Normalized Difference Bareness Index)	Measures soil or bare land exposure.	[107, 108]
	EBBI (Enhanced Built-up and Bareness Index)	Separates built-up from bare areas using multispectral bands.	[109]

Categories	Methods or Tools or Data	Descriptions	References
Spatial Metrics (Landscape Analysis)	Landscape metrics (fragmentation, dominance, connectivity, diversity)	Quantify spatial characteristics of landscapes, including structure, heterogeneity, and patterns of urbanization.	[110–115]
	FRAGSTATS software	Computes landscape fragmentation and structural metrics.	[116]
	LecoS plugin (QGIS)	Python-based tool for automated landscape ecology analysis.	[117]
	Patch Analyst (ArcGIS)	Quantifies fragmentation and landscape patterns.	[118–120]
Urban Dynamics Modelling	Cellular Automata (CA) models	Simulate urban growth using transition rules; implemented in TerrSet or combined with gravity models.	[121–124]
Urban Growth Models (Free or publicly available)	CLUE Series / General category	Models land-use conversion and environmental effects.	[126, 127]
	DINAMICA EGO / Forest category	Simulation of landscape change, especially forest dynamics.	[128]
	GeoSOS / Urban category	Provides urban sustainability decision-making modules.	[129]
	OBEUS / Urban category	Object-based simulation of urban environments.	[130]
	SLEUTH / Forest category	Widely used CA-based urban growth model (slope, land cover, exclusion, urbanization, transportation, hillshade).	[131]
	UrbanSim / Urban category	Agent-based urban simulation platform.	[132]

sion of Land Use and its Effects), and DINAMICA (Environment for Geoprocessing Objects). There are hybrid models that combine features of both approaches, such as GeoSOS (Geographical Simulation and Optimization Systems) and OBEUS. Notably, GeoSOS offers multiple modules designed to support decision-making for sustainable urban development, providing a versatile platform for simulating urban expansion and assessing planning alternatives.

3.2.4. Climate change in urban areas effects

Cities are increasingly at the front line of climate change, and researchers use a diverse set of tools to understand how urban areas are being reshaped by rising temperatures, shifting rainfall patterns, and growing environmental risks. The table below (Table 4) highlights the main approaches found in climate-impact studies, spanning physical measurements from satellite data, statistical analyses of long-term climate trends, and surveys that capture how people perceive these changes. Together, these methods provide a multifaceted picture of how climate change unfolds in urban settings and how communities respond to its challenges.

This section analyzes methods for studying climate change effects in urban environments. Out of publications, 80 focused on climate change impacts, accounting for approximately 18.18 % of datasets (Table 4).

Most of methods focus on urban heat island effects and precipitation patterns, reflecting their prominence in climate impact studies by using LST (Land Surface Temperature) and SPEI (Standardized Precipitation Evapotranspiration Index).

Surveys and perceptions on climate change in city were also used to capture local experiences, provide a socio-ecological context, but quantitative details are sometimes lacking. In the context of simulating future climate scenarios, models and projections have been used, but these were limited by data availability and technical requirements.

4. CONCLUSION

This bibliometric synthesis provides an integrated overview of the evolution of research on urban biodiversity, ecosystem services, land-use dynamics, and climate change impacts from 1990 to 2024, based on 345 publications. Clear temporal and spatial trends emerge that scientific production has accelerated since the early 2000s, peaking in 2017, with Asia (China and India) becoming the principal contributor, while Europe, Africa, and the Americas show variable yet substantial engagement.

Table 4. Methods for assessing climate change effects in urban environments
Tabela 4. Metody oceny skutków zmian klimatu w środowiskach miejskich

Category	Methods or Tools or Indicators	Descriptions	References
General Scope of Climate Change Impact Studies	Urban climate impact assessment	Examines environmental, social, and economic impacts of climate change on cities, including rising temperatures, extreme weather, and sea-level rise.	[133–141]
	Urban heat island (UHI) analysis	Focus on temperature amplification in cities, linked to increased energy demand, air pollution, and health risks.	[136–138]
	Urban flooding and precipitation impacts	Studies effects of intense precipitation, rising water levels, and impacts on infrastructure and essential services.	[139, 140]
Remote Sensing–Based Indicators	LST (Land Surface Temperature)	Key index for studying urban heat island intensity; used to analyze surface–atmosphere energy exchanges.	[146, 147]
	SPEI (Standardized Precipitation Evapotranspiration Index)	Used to assess drought, precipitation variability, and climate anomalies.	[144]
Quantitative Climate Analysis Methods	Statistical precipitation analysis	Includes Buishand's test, Hubert segmentation, linear regression, and Mann–Kendall slope analysis to detect trends in precipitation.	[144]
	Temperature trend diagnosis	Uses meteorological data to calculate statistical indices and analyze temperature changes over specific periods.	[145]
Socio-Ecological Methods	Surveys on climate change perception	Random sampling and survey questionnaires to capture local perceptions of climate change; analyzed using binary logistic regression (STATA® 13.1).	[142] [143]

Regarding urban biodiversity, field-based assessments remain dominant, although the use of remote sensing and biodiversity indices has expanded due to their ability to provide standardized and spatially explicit data. Persistent methodological fragmentation and weak integration of biodiversity indicators into urban planning still limit progress. Research on ecosystem services demonstrates diversified methodological approaches, combining biophysical, economic, and socio-ecological assessments, with integrated modelling tools such as InVEST increasingly used for spatialization and scenario analysis. Yet, harmonized methodologies and systematic uncertainty evaluation remain insufficient.

Studies addressing climate change impacts in urban areas have increased considerably, increasingly combining thermal indices, climate indicators, land-use dynamics, and socio-economic factors. However, predictive and operational tools to support local adaptation are still underdeveloped.

Overall, research has shifted from isolated thematic studies to interdisciplinary, multi-scalar approaches integrating ecological, climatic, and socio-spatial dimensions. Current trends highlight the growing importance of resilience-oriented planning, equity in ecosystem service provision, and nature-based solutions. Key challenges ahead include improving data accessibility, standardizing methods, and strengthening science-policy interfaces to support sustainable and resilient urban development.

FUNDING

The authors declare that this research received no specific grant from any funding agency, whether public, commercial, or not-for-profit.

ACKNOWLEDGMENTS

Authors thank Laboratory of Botany and Plant Ecology (LBEV) of University of Lomé (UL) for their unconditional and technical support.

REFERENCES

1. Elmqvist, T., Setälä, H., Handel, S.N., van der Ploeg, S., Aronson, J., Blignaut, J.N., Gómez-Baggethun, E., Nowak, D.J., Kronenberg, J., de Groot, R. Benefits of restoring ecosystem services in urban areas. Current opinion in environmental sustainability, 2015; volume 14: pp. 101–108.
2. Langemeyer, J.,. Gómez-Baggethun, E. Urban biodiversity and ecosystem services. Urban biodiversity. From research to practice, 2018; pp. 36–53.
3. Francis, R.A., Chadwick, M.A. Urban ecosystems: understanding the human environment. 2013; Routledge.
4. Shwartz, A.,Turbé, A., Julliard, R., Simon, L., Prévot, A.C. Outstanding challenges for urban conservation research and action. Global environmental change, 2014; volume 28, pp. 39–49.
5. Yang, L., Zhang, L., Li, Y., Wu, S. Water-related ecosystem services provided by urban green space: A case study in Yixing City (China). Landscape and urban planning, 2015; volume 136, pp. 40–51.
6. Boyd, E. Juhola, S. Adaptive climate change governance for urban resilience. Urban studies, 2015; volume 52(7), pp. 1234–1264.
7. Allam, Z., Jones, D., Thondoo, M. Cities and climate change: Climate policy, economic resilience and urban sustainability. 2020, Springer.
8. Adegboyega, S., Oloukoi, J., Olajuyigbe, A.E. Evaluation of unsustainable land use/land cover change on ecosystem services in coastal area of Lagos state, Nigeria. Applied Geomatics, 2019, volume 11, pp. 97–110.
9. Grimm, N.B., Faeth, S.H., Golubiewski, N.E. Global change and the ecology of cities. science, 2008; volume 319(5864), pp. 756–760.
10. Weiskopf, S.R., Rubenstein, M.A., Crozier, L.G., Gaichas, S., Griffis, R., Halofsky, J.E., Hyde, K.J.W., Morelli, T.L., Morisette, J.T., Munoz, R.C., Pershing, A.J., Peterson, D.L., Poudel, R., Staudinger, M.D., Sutton-Grier, A.E., Thompson, L., Vose, J., Weltzin, J.F., Whyte, K.P. Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. Science of the Total Environment, 2020; volume 733, pp. 137782.
11. Bakure, B.Z., Hundera, K., Abara, M. Review on the effect of climate change on ecosystem services. in IOP Conference Series: Earth and Environmental Science. 2022; IOP Publishing.
12. Seto, K.C., Güneralp, B., Hutyra, L.R. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proceedings of the National Academy of Sciences, 2012; volume 109(40), pp. 16083–16088.
13. Encaoua, D., Foray, D., Hatchuel, A., Mairesse, J. Les enjeux économiques de l'innovation: Bilan du programme CNRS. Revue d'économie politique, 2004, volume 114(2), pp. 133––168.
14. Storup, B., Millot, G., Neubauer, C. La recherche participative comme mode de production de savoirs. Un état des lieux des pratiques en France, Paris: Fondation Sciences Citoyennes, 2013.
15. Rostaing, H. La bibliométrie et ses techniques. 1996: Sciences de la Société; Centre de Recherche Rétrospective de Marseille.
16. Maddi, A. La quantification de la recherche scientifique et ses enjeux: bases de données, indicateurs et cartographie des données bibliométriques. 2018, Université Sorbonne Paris Cité.
17. Okubo, Y. Indicateurs bibliométriques et analyse des systèmes de recherche: méthodes et exemples, 1997.
18. Cuyala, S. Analyse spatio-temporelle d'un mouvement scientifique. L'exemple de la géographie théorique et quantitative européenne francophone. 2014, Université Paris 1 Panthéon-Sorbonne.
19. Hetu, M. La bibliométrie et l'innovation: l'étude de l'impact de la propriété intellectuelle sur le progrès scientifique. Ethics, Medicine and Public Health, 2018; volume 4, pp. 81–86.
20. Liu, X., Bollen, J., Nelson, M.L., van de Sompel, H. Co-authorship networks in the digital library research community. Information processing & management, 2005; volume 41(6), pp. 1462–1480.
21. Schick-Makaroff, K., MacDonald, M., Plummer, M., Burgess, J., Neander, W. What synthesis methodology should I use? A review and analysis of approaches to research synthesis. AIMS public health, 2016; volume 3(1), pp. 172.
22. Wyborn, C., Louder, E., Harrison, J., Montambault, J., Montana, J., Ryan, M., Bednarek, A., Nesshöver, C., Pullin, A., Reed, M., Dellecker, E., Kramer, J., Boyd, J., Dellecker, A., Hutton, J. Understanding the impacts of research synthesis. Environmental Science & Policy, 2018; volume 86, pp. 72–84.
23. Harzing, A.W. The publish or perish book. 2010: Tarma Software Research Pty Limited Melbourne, Australia.
24. OECD. Gross domestic spending on R&D. 2020; Available from: (https://www.oecd.org/en/countries/china-people-s-republic-of.html).
25. Brennan, J., Broek, S., Durazzi, N., Kamphuis, B., Ranga, M. Steve R. Study on innovation in higher education. Publications Office of the European Union, Luxembourg, 2014.
26. Hrabowski, F.A. Institutional change in higher education: Innovation and collaboration. Peabody Journal of Education, 2014; volume 89(3), pp. 291–304.
27. Kouadio, Y.J.C., Vroh, B.T.A., Bi, Z.B.G., Yao, Y.C.A. Évaluation de la diversité et estimation de la biomasse des arbres d'alignement des communes du Plateau et de Cocody (Abidjan-Côte d'Ivoire). Journal of Applied Biosciences, 2016; volume 97, pp. 9141–9151.
28. Sehoun, L.C., Osseni, A.A., Orounladji, M., Lougbegnon, T.O., Codjia, J.C.T. Diversité floristique des formations végétales urbaines au Sud du Bénin (Afrique de l'Ouest). Revue Marocaine des Sciences Agronomiques et Vétérinaires, 2021; volume 9(2), pp. 266–273.
29. Kabanyegeye, H., Ndayishimiye, J., Hakizimana, P., Masharabu, T., Malaisse, F., Bogaert, J. Diversité floristique et statut de conservation des espaces verts de la ville de Bujumbura (Burundi). Geo-Eco-Trop: Revue Internationale de Géologie, de Géographie et d'Écologie Tropicales, 2022; volume 46(1), pp. 15–28.

30. Charahabil, M.M., Bassene, C., Balde, H., Ndiaye, S. Diversité et structure des espaces végétalisés urbains de la ville de Ziguinchor, Sénégal. International Journal of Biological and Chemical Sciences, 2018; volume 12(4), pp. 1650–1666.
31. Mehraj, G., Khuroo, A.A., Hamid, M., Muzafar, I., Rashid, I., Malik, A.H. Floristic diversity and correlates of naturalization of alien flora in urban green spaces of Srinagar city. Urban Ecosystems, 2021; volume 24, pp. 1–14.
32. Kleeschulte, S., Gregor, M., Ayanu, Y., Jochen, A., Jaeger, G., Nazarnia, N., Paganini, M. Earth Observation in Support of the City Biodiversity Index. 2016.
33. Titeux, N., Henle, K., Mihoub, J.B., Regos, A., Geijzendorffer, I.R., Ctamer, W., Verburg, P.H., Brotons, L. Biodiversity scenarios neglect future land-use changes. Global change biology, 2016; volume 22(7), pp. 2505–2515.
34. Alkemade, R., van Oorschot, M., Miles, L., Nellemann, C. GLOBIO3: a framework to investigate options for reducing global terrestrial biodiversity loss. Ecosystems, 2009; volume 12, pp. 374–390.
35. Ten Brink, B., Tekelenburg, T. Biodiversity: how much is left. The Natural Capital Index framework (NCI). RIVM report, 2002. 402001014.
36. Scholes, R.J. Biggs, R. A biodiversity intactness index. Nature, 2005; volume 434(7029), pp. 45–49.
37. Certain, G., Skarpaas, O., Bjerke, J.W., Framstad, E. The Nature Index: A general framework for synthesizing knowledge on the state of biodiversity. PLoS One, 2011; volume 6(4), e18930.
38. Yun, H., Park, J., Choi, T., Choi, I. A review on applicability of sustainable city index-focusing on GCI, EPI and CBI. Journal of environmental impact assessment, 2015; volume 24(6), pp. 593–606.
39. Uchiyama, Y., Hayashi, K., Kohsaka, R. Typology of cities based on city biodiversity index: exploring biodiversity potentials and possible collaborations among Japanese cities. Sustainability, 2015; volume 7(10), pp. 14371–14384.
40. Bhattacharya, T. Comparative assessment of ecosystem and biodiversity conservation measures in Indian smart cities: a city biodiversity index approach. Int J Sustain Futur Hum Secur, 2017; volume 5(2), pp. 18.
41. Sahani, S., Raghavaswamy, V. Analyzing urban landscape with City Biodiversity Index for sustainable urban growth. Environmental Monitoring and Assessment, 2018; volume 190, pp. 1–18.
42. Amarasinghe, N.S., Perera. P.K.P. Application of the City Biodiversity Index: A Sri Lankan Case Study. 2018.
43. Chernyshenko, O., Frolova, V.A., Zhdanova, L.P. UN strategy and ecosystem sustainability indicators for preserving Moscow's urban biodiversity. FORESTRY BULLETIN, 2021.
44. MEA, Ecosystems and human well-being: wetlands and water. 2005: World Resources Institute.
45. TEEB, Ecological and economic foundation. 2010, The UK National Ecosystem Assessment Technical Report. UNEP--WCMC, Cambridge: Earthscan, Cambridge. UK NEA, 2011.
46. O'Farrell, P. Évaluation des services écosystémiques dans les zones urbaines. 2ème édition ed. Le manuel Routledge d'écologie urbaine. 2020.
47. Boyd, J. Services écosystémiques : évaluation. Écosystèmes terrestres et biodiversité, 2020, volume 2, CRC Presse.
48. Zhao, X., Hu, W., Han, J., Wei, W., Xu, J. Urban Above-Ground Biomass Estimation Using GEDI Laser Data and Optical Remote Sensing Images. Remote Sensing, 2024; volume 16(7), 1229.
49. Naidoo, R., Balmford, A., Costanza, R., Fisher, B., Green, r.E., Lehner, B., Malcolm, T.R., Rickett, T.H. Global mapping of ecosystem services and conservation priorities. Proceedings of the National Academy of Sciences, 2008; volume 105(28), pp. 9495–9500.
50. Schulp, C.J., Alkemade, R., Petz, K., Goldewijk, K.K. Mapping ecosystem functions and services in Eastern Europe using global-scale data sets. International Journal of Biodiversity Science, Ecosystem Services & Management, 2012; volume 8(1–2), pp. 156–168.
51. Lasseur, R. Cartographie multi-échelles des services écosystémiques: caractérisation des associations spatiales et apports de la télédétection. 2017, Université Grenoble Alpes.
52. Pelorosso, R., Gobattoni, F., Geri, F., Leone, A. PANDORA 3.0 plugin. 2017.
53. Wunder, S., Wertz-Kanounnikoff, S. Payments for ecosystem services: a new way of conserving biodiversity in forests. Journal of Sustainable Forestry, 2009; volume 28(3–5), pp. 576–596.
54. Bhatta, L.D., Helmuth, Bob, E., van Oort, H., Rucevska, I., Baral, H. Payment for ecosystem services: possible instrument for managing ecosystem services in Nepal. International Journal of Biodiversity Science, Ecosystem Services & Management, 2014; volume 10(4), pp. 289–299.
55. Selmi, W. Ecosystem services provided by urban vegetation: Application of assessment approaches in Strasbourg city. Services écosystémiques rendus par la végétation urbaine Application d'approches d'évaluation à la ville de Strasbourg. 2014, Université de Strasbourg.
56. de Groot, R.S., Alkemade, R., Braat, L., Hein, L., Willemen, L. Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. Ecological complexity, 2010; volume 7(3), pp. 260–272.
57. Wainger, L., Mazzotta, M. Realizing the potential of ecosystem services: a framework for relating ecological changes to economic benefits. Environmental management, 2011; volume 48, pp. 710–733.
58. Dixon, J., Pagiola, S. Analyse économique et évaluation environnementale. 1998.
59. Colon, M., Mattersdorf, G., Pavageau, C. La place de l'évaluation économique de la biodiversité et des services écosystémiques dans les processus de décision. Nancy, France, AgroParisTech/IDDRI, 2009.
60. Dupras, J. Évaluation économique des services écosystémiques dans la région de Montréal: analyse spatiale et préférences exprimées, 2014.
61. Ndiaye, L. Perception communautaire sur la diversité floristique et les biens et services écosystémiques fournis par la végétation ligneuse dans la commune de Coumbacara (Kolda, Sénégal), 2020.

62. Riechers, M., Barkmann, J., Tscharntke, T. Perceptions of cultural ecosystem services from urban green. Ecosystem Services, 2016; volume 17, pp. 33–39.
63. Kabanyegeye, H., Masharabu, T., Sikuzani, Y.U., Bogaert, J. Perception sur les espaces verts et leurs services écosystémiques par les acteurs locaux de la ville de Bujumbura (République du Burundi). Tropicultura, 2020; volume 38(3–4).
64. Wessels, N., Sitas, N., Esler, K., o'Farrell, P. Understanding community perceptions of a natural open space system for urban conservation and stewardship in a metropolitan city in Africa. Environmental Conservation, 2021; volume 48(4), pp. 244–254.
65. Ouédraogo, I., Blandine, M., Nacoulma, I., Hahn, K., Thiombiano, A. Assessing ecosystem services based on indigenous knowledge in south-eastern Burkina Faso (West Africa). International Journal of Biodiversity Science, Ecosystem Services & Management, 2014; volume 10(4), pp. 313–321.
66. Plieninger, T., Dijks, S., Oteros Rozas, E., Bieling, C. Assessing, mapping, and quantifying cultural ecosystem services at community level. Land use policy, 2013; volume 33, pp. 118–129.
67. McPhearson, T., Kremer, P., Hamstead, Z.A. Mapping ecosystem services in New York City: Applying a social–ecological approach in urban vacant land. Ecosystem Services, 2013; volume 5, pp. 11–26.
68. Burkhard, B., Kroll, F., Nedkov, S., Müller, F. Mapping ecosystem service supply, demand and budgets. Ecological indicators, 2012; volume 21, pp. 17–29.
69. Martínez-Harms, M.J., Balvanera, P. Methods for mapping ecosystem service supply: a review. International Journal of Biodiversity Science, Ecosystem Services & Management, 2012; volume 8(1–2), pp. 17–25.
70. Hou, Y., Burkhard, B., Müller, F. Uncertainties in landscape analysis and ecosystem service assessment. Journal of environmental management, 2013; volume 127, pp. 117–131.
71. Yang, D., Liu, W., Tang, L., Chen, L., Li, X., Xu, X. Estimation of water provision service for monsoon catchments of South China: Applicability of the InVEST model. Landscape and Urban Planning, 2019; volume 182, pp. 133–143.
72. Wu, L., Sun, C., Fan, F. Estimating the characteristic spatiotemporal variation in habitat quality using the invest model—A case study from Guangdong–Hong Kong–Macao Greater Bay Area. Remote Sensing, 2021; volume 13(5), pp. 1008.
73. Zhong, Y., Lin, A., He, L., Zhou, Z., Yuan, M. Spatiotemporal dynamics and driving forces of urban land-use expansion: A case study of the Yangtze River economic belt, China. Remote Sensing, 2020; volume 12(2), pp. 1–26.
74. Shao, M., Wu, L., Li, F., Lin, C. Spatiotemporal dynamics of ecosystem services and the driving factors in urban agglomerations: Evidence from 12 National Urban Agglomerations in China. Frontiers in Ecology and Evolution, 2022; volume 10, p. 804969.
75. Peng, L., Zhang, L., Li, Z., Wang, P., Zhao, W., Wang, Z., Jiao, L., Wang, H. Spatio-temporal patterns of ecosystem services provided by urban green spaces and their equity along urban–rural gradients in the Xi'an Metropolitan Area, China. Remote Sensing, 2022; volume 14(17), p. 4299.
76. Weisstein, E.W., Gini coefficient, 2000. (https://mathworld. wolfram. com/).
77. Tooke, T.R., Klinkenberg, B., Coops, N.C. A geographical approach to identifying vegetation-related environmental equity in Canadian cities. Environment and Planning B: Planning and Design, 2010; volume 37(6), pp. 1040–1056.
78. Fotheringham, A.S., Brunsdon, C., Charlton, M. Geographically weighted regression. The Sage handbook of spatial analysis, 2009; volume 1, pp. 243–254.
79. Han, B., Ouyang, Z. The comparing and applying Intelligent Urban Ecosystem Management System (IUEMS) on ecosystem services assessment. Acta Ecol. Sin, 2021; volume 41, pp. 8697–8708.
80. Clauzel, C. Dynamiques de l'occupation du sol et mutations des usages dans les zones humides urbaines. Étude comparée des hortillonnages d'Amiens (France) et des chinampas de Xochimilco (Mexique), 2008, Université Paris-Sorbonne-Paris IV.
81. Bonhomme, M., Création d'un outil d'aide à la décision pour un aménagement durable des espaces verts dans les municipalités, 2012, Université de Sherbrooke.
82. Compaoré, G., Nebié, O. Croissance démographique et espace urbain à Ouagadougou (Burkina Faso). Centre de Recherches sur les espaces Tropicaux, Études urbaines à Ouagadougou–Burkina Faso, Bordeaux, CRET, 2003; volume 11, pp. 9–28.
83. Boyer, F. Croissance urbaine, statut migratoire et choix résidentiels des Ouagalais. Vers une insertion urbaine ségrégée? Revue Tiers Monde, 2010(1); pp. 47–64.
84. Gallez, C., Maksim, H.N. À quoi sert la planification urbaine? Flux, 2007; volume 69(3), pp. 49–62.
85. Oladokoun, A., Ayoh, A., Atchade, A.J., Fandjinou, K. Patterns of urban ecology and sustainability challenges in Togo cities, West Africa. Applied Ecology & Environmental Research, 2024; volume 22(2), pp. 1711–1731.
86. Coutard, O., Rutherford, J. Vers l'essor de villes «post--réseaux»: infrastructures, innovation sociotechnique et transition urbaine en Europe». L'innovation face aux défis environnementaux de la ville contemporaine, 2013; pp. 97––118.
87. Mangin, G., Marchal,H., Vincent, S. Les formes contemporaines de la mobilité. Espace populations sociétés. Space populations societies, 2023(2023/2).
88. Guérois, M., Paulus, F. Commune centre, agglomération, aire urbaine: quelle pertinence pour l'étude des villes? Cybergeo, 2002; volume 212, p. 15.
89. Leducq, D., Ananian, P. Qu'apporte l'urbanisme à l'étude des espaces de coworking? Revue de littérature et approche renouvelée. Économie Régionale et Urbaine, 2019; volume 5, pp. 963–986.
90. Sudhira, H., Ramachandra, T., Jagadish, K. Urban sprawl: metrics, dynamics and modelling using GIS. International Journal of Applied Earth Observation and Geoinformation, 2004; volume 5(1), p. 29–39.
91. Zhang, Q., Wang, J. A rule-based urban land use inferring method for fine-resolution multispectral imagery. Canadian Journal of Remote Sensing, 2003; volume 29(1), pp. 1–13.

92. Berrada, A., He, D.C., Morin, D. Identification des piscines à l'aide d'une image ikonos: cas de la ville de Sherbrooke (Québec). Revue Télédétection, 2007; volume 1, pp. 2–3.
93. Wang, D., He, D.C., Wang, L., Morin, D. L'extraction du réseau routier urbain à partir d'images SPOT HRV. International Journal of Remote Sensing, 1996; volume 17(4), pp. 827–833.
94. Zhang, Q., Seto, K.C. Mapping urbanization dynamics at regional and global scales using multi-temporal DMSP/OLS nighttime light data. Remote Sensing of Environment, 2011; volume 115(9), p. 2320–2329.
95. Demaze, M.T. Un panorama de la télédétection de l'étalement urbain. ESO Travaux et Documents, 2010; volume 29, pp. 99–124.
96. Lang, F.M. Suivi des changements des utilisations/occupations du sol en milieu urbain par imagerie satellitale de résolution spatiale moyenne: Le cas de la région métropolitaine de Montréal. 2012.
97. Charfi, S., Dahech, S. Cartographie des températures à Tunis par modélisation statistique et télédétection. Mappemonde. Revue trimestrielle sur l'image géographique et les formes du territoire, 2018(123).
98. Marou, M., Elyaagoubi, M. Agriculture urbaine entre ancrage territorial et défis de l'urbanisation: cas de la ville de Guercif (Maroc oriental). Territoires, Environnement et Développement (TED), 2024; volume 3(1), p. 27–36.
99. Carine, N.M.A., Ta, M.Y., Armel, K.K., Satti, K. Cartographie des unités d'occupation du sol du District d'Abidjan depuis le cloud Google Earth Engine, sur la base des images optiques Sentinel-2 et des algorithmes de Machine Learning. International Journal of Innovation and Applied Studies, 2023; volume 40(1), pp. 310–332.
100. El Garouani, A., Aharik, K. Apport des images LANDSAT à l'étude de l'évolution de l'occupation du sol dans la plaine de SAÏSS au MAROC, pour la période 1987–2018. Revue Française de Photogrammétrie et de Télédétection, 2021; volume 223(1), pp. 173–188.
101. Mba, B.M.M., Pennober, G., Revillion, C., Rouet, P., David, G. Estimations, à partir de séries d'images LANDSAT, des évolutions de stocks de carbone de différentes formations en milieu équatorial côtier-cas de Libreville au Gabon. Revue Française de Photogrammétrie et de Télédétection, 2022; volume 223, p. 217–231.
102. Xu, H. A new index for delineating built-up land features in satellite imagery. International journal of remote sensing, 2008; volume 29(14), pp. 4269–4276.
103. Khallef, B., Brahamia, K., Oularbi, A.R. Application des indices de télédétection à la cartographie des zones urbaines et des sols nus: Cas de la ville de Guelma (Nord-est de L'Algérie). International Journal of Innovation and Applied Studies, 2020; volume 28(2), pp. 452–457.
104. Rouse Jr, J.W. Monitoring the vernal advancement and retrogradation (green wave effect) of natural vegetation. 1974.
105. Zha, Y., Gao, J., Ni, S. Use of normalized difference built-up index in automatically mapping urban areas from TM imagery. International journal of remote sensing, 2003; volume 24(3), pp. 583–594.
106. Khomarudin, M.R. Tsunami Risk and Vulnerability, 2010.
107. Zhao, H., Chen, X. Use of normalized difference bareness index in quickly mapping bare areas from TM/ETM+. in International geoscience and remote sensing symposium. 2005.
108. Yulianto, F., Tjahjono, B., Anwar, S. Detection settlements and population distribution using GIS and remotely sensed data, in the surrounding area of Merapi Volcano, Central Java, Indonesia. Int J Emerg Technol Adv Eng, 2014; volume 4(3), pp. 1–10.
109. As-Syakur, A.R., Adnyana, I.W.S., Arthana, I.W., Nuarsa, I.W. Enhanced built-up and bareness index (EBBI) for mapping built-up and bare land in an urban area. Remote sensing, 2012; volume 4(10), pp. 2957–2970.
110. Sammari, H. Développement d'une méthode d'automate cellulaire basé sur une tessellation irrégulière et hiérarchique pour la simulation des processus spatiotemporels, 2014.
111. Essid, H. Modélisation spatio-temporelle à base de modèles de Markov cachés pour la prévision des changements en imagerie satellitaire: cas de la végétation et de l'urbain, 2012, Université Blaise Pascal-Clermont-Ferrand II.
112. Grossetti, M. Les effets de proximité spatiale dans les relations entre organisations: une question d'encastrements. Espace et Société, 2000; volume 101–102, pp. 203–219.
113. Oliveau, S. Autocorrélation spatiale: leçons du changement d'échelle. Espace géographique, 2010; volume 39(1), pp. 51–64.
114. Wu, J., Jelinski, D.E., Luck, M.A., Tueller, P.T. Multiscale analysis of landscape heterogeneity: scale variance and pattern metrics. Geographic information sciences, 2000; volume 6(1), pp. 6–19.
115. Oszwald, J., Gond, V., Dolédec, S., Lavelle, P. Identification d'indicateurs de changement d'occupation du sol pour le suivi des mosaïques paysagères. Bois et forêts des tropiques, 2011; volume 307(1), pp. 7–21.
116. McGarigal, K. FRAGSTATS: spatial pattern analysis program for quantifying landscape structure. US Department of Agriculture, Forest Service, Pacific Northwest Research Station, 1995; volume 351.
117. Jung, M. LecoS—A python plugin for automated landscape ecology analysis. Ecological informatics, 2016; volume 31, pp. 18–21.
118. Subirós, J.V., Welch, J.M. La homogeneización paisajística de los valles de Hortmoier y Sant Aniol (Alta Garrotxa. Girona): Caracterización y evaluación de los cambios ambientales en el período 1957–1979–1996 con Patch Analyst. in Actas del XVII Congreso de Geógrafos Españoles: Oviedo, noviembre de 2001, 2001. Departamento de Geografía.
119. Junfei, L.W., Yanming, L., Jia, G., Wei L., Yanhua, B. Évaluation de l'indice de configuration du paysage des parcs urbains de Pékin basée sur Patch Analyst. Environnement urbain et écologie urbaine, 2007; volume 6, pp. 14–16.
120. Baral, H., Keenan, R.J., Sharma, S.K., Stork, N.E., Kasel, S. Spatial assessment and mapping of biodiversity and conservation priorities in a heavily modified and fragmented

production landscape in north-central Victoria, Australia. Ecological Indicators, 2014; volume 36, pp. 552–562.
121. Battya, M., Xieb, Y., Sunc, Z. Modeling urban dynamics through GIS-based cellular automata. Computers, Environment and Urban Systems, 1999; volume 23(205), p. 233.
122. Xie, Y., Sun, Z. Modeling urban dynamics through GIS-based cellular automata. Computers, environment and urban systems, 1999; volume 23(3), pp. 205–233.
123. He, C., Zhao, Y., Tian, J., Shi. Modeling the urban landscape dynamics in a megalopolitan cluster area by incorporating a gravitational field model with cellular automata. Landscape and Urban planning, 2013; volume 113, pp. 78–89.
124. He, C., Zhang, D., Huang, Q., Zhao, Y. Assessing the potential impacts of urban expansion on regional carbon storage by linking the LUSD-urban and InVEST models. Environmental Modelling & Software, 2016; volume 75, pp. 44–58.
125. Li, X., Gong, P. Urban growth models: progress and perspective. Science bulletin, 2016; volume 61, pp. 1637––1650.
126. Verburg, P.H., Soepboer, W., Veldkamp, A., Limpiada, R., Espaldon, V., Mastura, S.S.A. Modeling the spatial dynamics of regional land use: the CLUE-S model. Environmental management, 2002; volume 30, pp. 391–405.
127. Verburg, P.H., Overmars, K.P. Combining top-down and bottom-up dynamics in land use modeling: exploring the future of abandoned farmlands in Europe with the Dyna-CLUE model. Landscape ecology, 2009; volume 24, pp. 1167–1181.
128. Soares-Filho, B.S., Cerqueira, G.C., Pennachin, C.L. DINAMICA—a stochastic cellular automata model designed to simulate the landscape dynamics in an Amazonian colonization frontier. Ecological modelling, 2002; volume 154(3), pp. 217–235.
129. Li, X., Chen, Y., Liu, X., Li, D. Concepts, methodologies, and tools of an integrated geographical simulation and optimization system. International Journal of Geographical Information Science, 2011; volume 25(4), pp. 633–655.
130. Torrens, P.M., Benenson, I. Geographic automata systems. International Journal of Geographical Information Science, 2005; volume 19(4), pp. 385–412.
131. Clarke, K.C., Hoppen, S., Gaydos, L. A self-modifying cellular automaton model of historical urbanization in the San Francisco Bay area. Environment and planning B: Planning and design, 1997; volume 24(2), pp. 247–261.
132. Waddell, P. UrbanSim: Modeling urban development for land use, transportation, and environmental planning. Journal of the American planning association, 2002; volume 68(3), pp. 297–314.
133. Satterthwaite, D., Huq, S., Pelling, M., Reid, H., Lankao, P.R. Adapting to Climate Change in Urban Areas: The Possibilities and Constraints in Low-and Middle-Income Nations1, in Adapting cities to climate change, Routledge, 2012; pp. 3–47.
134. Mooney, H., Larigauderie, A., Cesario, M., Elmqvist, T., Hoegh-Guldberg, O., Lavorel, S., Mace, G.M., Palmer, M., Sholes, R.J., Yahara, T. Biodiversity, climate change, and ecosystem services. Current opinion in environmental sustainability, 2009; volume 1(1), pp. 46–54.
135. Kumar, P. Climate change and cities: challenges ahead. Frontiers in Sustainable Cities, 2021; volume 3, p. 645613.
136. Oke, T.R. The energetic basis of the urban heat island. Quarterly journal of the royal meteorological society, 1982; volume 108(455), pp. 1–24.
137. Knowles, C.L. Planning Strategies for Improving Resilience of Cities in Developing Countries to the Urban Heat Island, 2020.
138. Hajat, S., O'Connor, M., Kosatsky, T. Health effects of hot weather: from awareness of risk factors to effective health protection. The Lancet, 2010; volume 375(9717), pp. 856––863.
139. Nicholls, R.J., Cazenave, A. Sea-level rise and its impact on coastal zones. science, 2010; volume 328(5985), pp. 1517–1520.
140. Kundzewicz, Z.W., Kanae, S.., Seneviratne, S.I., Handmer, J., Nicholls, N., Peduzzi, P., Mechler, R., Bouwer, L.M., Arnell, N., Mach, K., Muir-Wood, R., Brakenridge, G.R., Kron, W., Benito, G., Honda, Y., Takahashi, K., Sherstyukov, B. Flood risk and climate change: global and regional perspectives. Hydrological Sciences Journal, 2014; volume 59(1), pp. 1–28.
141. Rosenzweig, C., Hammer, S.A., Mehrotra, S., Solecki, W.D. Climate change and cities: First assessment report of the urban climate change research network. 2011: Cambridge University Press.
142. Saeed, U., Arshad, M., Hayat, S., Morelli, T.L., Nawaz, M.A. Analysis of provisioning ecosystem services and perceptions of climate change for indigenous communities in the Western Himalayan Gurez Valley, Pakistan. Ecosystem Services, 2022; volume 56, p. 101453.
143. Kosmowski, F.,Lalou, R., Sultan, B., Ndiaye, O., Muller, B., Galle, S., Seguis, L. Observations et perceptions des changements climatiques. 2015, IRD.
144. Bedoum, A., Clobite, B., Mbanghoguinan, A., Issak, B.L. Impact de la variabilité pluviométrique et de la sécheresse au sud du Tchad: effets du changement climatique. Revue Ivoirienne des Sciences et Technologies, 2014; volume 23, pp. 13–30.
145. Badameli, A., Dubreuil, V. Diagnostic du changement climatique au Togo à travers l'évolution de la température entre 1961 et 2010. in XXVIIIe Colloque de l'association internationale de Climatologie, 2015.
146. Boudjellal, L., Bourbia, F. An evaluation of the cooling effect efficiency of the oasis structure in a Saharan town through remotely sensed data. International Journal of Environmental Studies, 2018; volume 75(2), pp. 309–320.
147. Gherraz, H., Alkama, D. L'estimation de l'impact des espaces verts et des surfaces d'eau sur le climat urbain et la temperature de surface du sol (Mila, Algérie). Romanian Journal of Geography/Revue Roumaine de Géographie, 2020; volume 64(2), pp. 155–174.