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GREEN METRICS: INTERNET OF THINGS BASED ECOLOGICAL MONITORING AND MANAGEMENT FOR SUSTAINABLE URBAN LIVING IN KYIV

Volodymyr Nazarenko[1], Ph.D. in Economics**;**

Andrii Martyn[2], Doctor of Economics/Professor;

Larisa Klikh[3], Doctor of Pedagogical Sciences; **Oksana Pashchenko**[4], Ph.D. in Economics

[1,2,3,4]National University of Life and Environmental Sciences of Ukraine

Abstract. Given the importance of the ecological component as part of the Internet of Things (IoT) green city platform, it is necessary to constantly monitor the ecological situation in the cities and sub-urban areas. The Kyiv city (Ukraine) has been chosen as a test subject for the study. As a part of sustainability process management systems, we focused on modelling and analysis of the green city service systems. Objective of the study is to research and compare various economic and ecological data from large cities; outline the scope of the green city model that is used for web service design, which is part of larger internet of things sustainable information system platform. The following categories of data had been processed, but not limited to the total cost of the system, the total loss of a natural resource, the amount of investment in restoration or maintenance, the cost of natural materials, oxygen supply, the price of conversion for the exploitation or destruction of a natural resource, land prices dynamics, the tax on the restoration of the territory, the total economic benefit from the territory and the volume of CO_2 emissions. Green City e-service platform has been constructed to enable the users to calculate the net cost, losses associated with natural resources available, and replenishment costs, both per unit of area and per unit of time. One of the most important outcomes of the service presented in this paper is the correlation between the urbanization processes (the increase in pollution, densification of buildings, the formation of agglomerations, new transportation, and infrastructure development) and their impact on the overall state of local ecosystems. The presented process management and monitoring service can further be enhanced to create a dynamic forecasting and situational assessment system as part of a green city management platform.

Key words: smart city, sustainable development, service economy, green city, e-platform.

JEL code: Q50, C80

Introduction

The interdependence between urban development and environmental transformation represents a critical nexus in contemporary urban studies. Urban expansion, characterized by the augmentation of city boundaries and suburban areas, exerts profound impacts on environmental quality, encompassing alterations in land use, heightened concentrations of planned infrastructure such as roads, and the strategic placement of industrial entities. This urban sprawl is concomitant with escalated emissions of pollutants and overall environmental degradation, manifesting in adverse health outcomes for inhabitants, as well as deleterious effects on local biodiversity, soil quality, and atmospheric conditions. A pivotal challenge in sustainable urban planning involves the comprehensive evaluation of the urban ecological footprint, encompassing an assessment of existing natural resources, their quality, and resilience in the face of dynamic alterations, including ecological catastrophes, military conflicts, technological disasters, and urban expansion (Loiseau, E., 2016; Victor, P. A., 2012). The criticality of the ecological dimension in urbanization research necessitates the ongoing surveillance of urban environments, predicated on standardized criteria that facilitate comparative analyses across diverse geographic locales, from densely populated cities to rural communities and unoccupied territories.

The ecological dynamics of urban areas are influenced by a multitude of factors, including the extent and conservation status of green spaces, urban sprawl, regional specificities, and the strategic positioning

[1] E-mail: volodnz@nubip.edu.ua Tel.: +380661260476, ORCID: https://orcid.org/0000-0002-7433-2484
[2] E-mail: martyn@nubip.edu.ua, ORCID: https://orcid.org/0000-0002-6905-2445
[3] E-mail: lklih@nubip.edu.ua, ORCID: https://orcid.org/0000-0001-5652-7168
[4] E-mail: opashchenko26@gmail.com, ORCID: https://orcid.org/0000-0002-0603-8072

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of industrial activities (Georgeson, L., 2017; Zhang, L., 2022). These elements collectively contribute to the urban ecological profile, necessitating a nuanced understanding of the primary drivers of urbanization and their prospective impacts on environmental health and sustainability.

In this context, the delineation of key parameters for urbanization studies is imperative, aiming to elucidate their influence on ecological outcomes and to project future environmental trajectories. The multifaceted interactions between land utilization—including forested areas, agricultural lands, and urban development-play a pivotal role in shaping the regional environmental landscape. Consequently, economic planning and development strategies must incorporate environmental considerations, forecasting the ecological ramifications of land resource exploitation and the construction of new industrial and residential complexes (Hammer, J., 2017).

The exigency for an integrated approach to environmental cost assessment within the framework of territorial and economic planning is underscored. Such an approach necessitates the collaboration of municipal authorities and territorial community councils in devising methodologies that quantify environmental losses and incorporate environmental costs into comprehensive planning models (Brilhante, O., 2018). This strategic orientation towards environmental stewardship within urban and territorial planning underscores the imperative for a balanced coalescence of economic development and environmental conservation, ensuring the sustainability of urban ecosystems in the face of escalating urbanization pressures (Jenks, M., 2009).

The aim of the study is to determine major ecology related metrics parameters based on real data from number of cities worldwide that will be used to model internet of things information monitoring and management system for future detailed development of Kyiv city sustainable development plan.

Materials and Methods

Exemplary instances of the integration of environmental sustainability within economic policy frameworks are observed in select urban centres globally, including but not limited to European Union cities such as Vienna, Copenhagen, Amsterdam, and Paris, as well as Singapore, specific municipalities in the United States, and at the national level in countries like Finland and Canada. These locales have embarked on comprehensive environmental initiatives that encompass the enhancement of municipal wastewater treatment infrastructures, the implementation of advanced waste treatment and recycling protocols, the restoration of agricultural lands, and the formulation of urban development strategies aligned with the principles of sustainable development.

To methodologically examine the urbanization phenomenon from a green economy perspective, a novel global framework has been proposed. This framework is underpinned by a sophisticated information model and leverages principal methodologies from ecological and economic research disciplines. It incorporates detailed schematics, methodological guidelines, and environmental monitoring data pertinent to the urbanization context. The model facilitates an in-depth analysis of environmental metrics, including waste management practices, carbon dioxide emission levels, and the preservation of green spaces across 13 strategically selected urban entities.

Furthermore, this approach entails a rigorous computation of the proportionality between total environmental expenditures and the aggregate economic outlays within these cities. This analytical research yields a comprehensive environmental and economic projection, charting a course towards sustainable development through to the year 2035. Such forward-looking assessments are pivotal in informing policy decisions and strategic planning, ensuring that urban development trajectories are sustainable, resilient, and conducive to the well-being of both the environment and urban populations.

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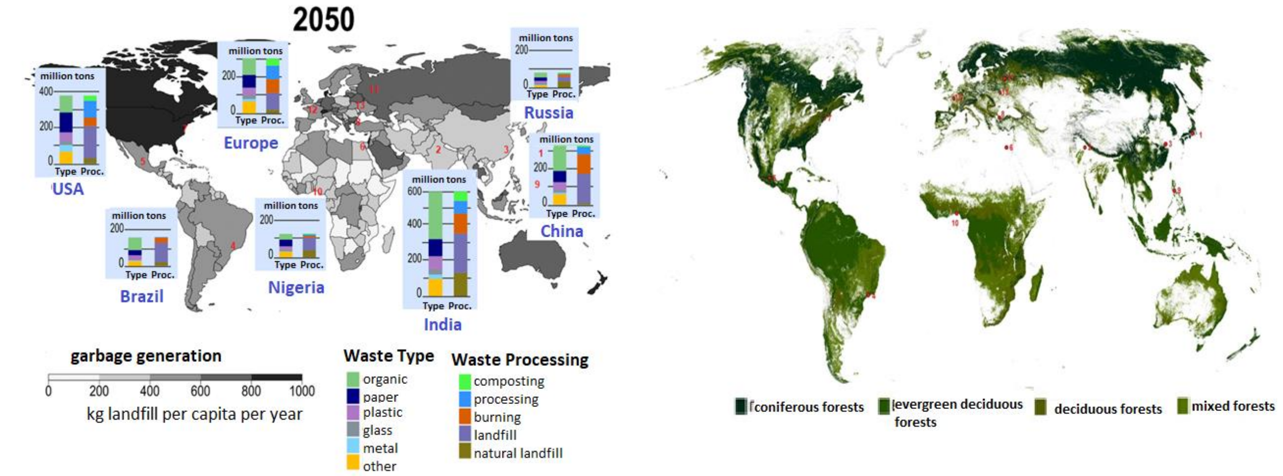

Source: Chen D.; World Bank, 2022

Fig. 1. **Forecast for 2050 on waste generation with its distribution by type and different options for waste recycling in the countries selected for research (left). Map of the current state of the world's forest cover by tree types and highlighted locations of selected cities (right)**

Figure 1 elucidates the outcomes of an extensive investigation into urban environmental management strategies, showcasing the integration of waste management systems, municipal initiatives for carbon dioxide (CO_2) emission reduction, and comprehensive plans for the cultivation and maintenance of urban green spaces within the cities under review (with the research dataset extending up to the year 2023). This study meticulously compiled, analysed, and synthesized key economic, social, financial, and environmental metrics to construct an information model elucidating the urbanization dynamics. This model served as a foundation for the application of system modelling techniques and the prognostication of land use evolution.

The research encompassed a global selection of 13 cities, alongside Kyiv, Ukraine, providing a diverse geographical and socio-economic scope. An analytical focus was placed on the year 2022, presenting a detailed comparison between the aggregate environmental expenditures and the overall financial outlays of the cities in question. Furthermore, the study ventures into predictive analytics, offering environmental and economic forecasts within the framework of a sustainable development agenda projected up to the year 2035. This forward-looking perspective aims to furnish policymakers, urban planners, and stakeholders with insights essential for aligning urban development trajectories with the principles of sustainability, thereby facilitating informed decision-making processes in urban governance and environmental stewardship.

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Table 1

Cities budget and ecology-related expenses

№	**City**	**Total City annual budget, $**	**Total city annual expenses, $**	**Waste collection and recycling costs, $**	**Emissions reduction policy social costs, $**	**Green covers annual expenses, $**
1	Kyiv	2433M.	2000M.	9.4M.	265M.	216.6M.
2	Paris	18500M.	12000M.	721M.	842.2M.	900M.
3	New York	101000M.	92500M.	9604M. 432M (export)	7850M.	891M.
4	Shanghai	287000M.	108000M.	1197M.	425M.	3245M.
5	Mexico City	11200M.	11200M.	156.5M.	300M.	224M.

Source: created by the authors based on their research

For detailed analytics and research, we focused on five cities for further studies (Table 1). For present calculations, official statistical and scientific data were used. The social cost of carbon emissions is $ 50 per ton, the optimal size of the green area is 9 square meters per city inhabitant, and 270 kg of waste per year per capita, according to average data from all over the world. Costs of waste collection and recycling for chosen cities - Kyiv (waste storage) - $9.44 per kg; Paris - €60 per kg; New York City- $686 per ton; Shanghai - $149 per kg; Mexico City $21.45 per kg. Green cover area in city zone: Kyiv – 450 km^2; Paris – 250 km^2; New York – 2546 km^2; Shanghai – 1201 km^2; Mexico City – 33 km^2. Part of total ecology-related expenses for picked cities is as follows for the 2035 plan - Kyiv – 7%; Paris – 25.4%; New York – 3.2%; Shanghai – 3%; Mexico City – 27.4%. Data presented in Table 1 proves that carbon emissions should be reduced as carbon emission reduction can take around 8.5% of the total city expenses (in NY city). Besides densely populated and heavily urbanized city now spend more than 900 million dollars annually to restore green coved within the city and its suburbs. These factors alone prove the need of a complex approach to model and improve sustainable development of the large cities. An analysis has been carried out and the main economic indicators of activity of enterprises in the agricultural and food industries have been calculated, which have been used to carry out an economic assessment of the consequences of urbanization processes and an analysis of the impact of various factors on urbanization. The above-mentioned research data and materials have been used to create a general green city concept model.

The development of the city and the change in the state of the environment in it are inextricably linked factors. The size of the city and the size of its suburbs have a huge impact on the environment, as well as the concentration of roads, the location of industrial enterprises, plants, factories, etc. And because of their activities, we have an increase in harmful emissions and pollution, which affects the health of residents, as well as the state of local flora and fauna, soil, and air. The development of urbanization also has a significant impact on water resources, the state of rivers, and reservoirs. There are many aspects to the economic costs associated with ecology expense policies. The list of the policies and their components are presented in Table 2. Among the most important are national or local tax policies, the costs of technological adaptation the cessation of deforestation, and the restoration of ecological biomass. Materials presented in Table 2 are basis for the green city conceptual model and are used to build IoT information system platform.

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Table 2

City ecology-related policies classification

№	Policy name	Policy Components	Data	Result of policy implementation
1	Urban economy and financial planning	Social and labor policies Total ecology-related budget Green taxes Land rant	Budget Price Cost	National expenditure on healthcare Quality of the environment
2	Sustainable land management	Property usage Land market surveillance	Green cover area Value of the property	Land cover changes Land usage optimization Land zoning and division
3	Power supply and resource consumption	Power supply efficiency Available resources Electricity production technology by source The level of taxation by technology	Price per unit Market price Taxe rate Annual emissions The ratio of green and fossil fuel energy	The cost of electricity production The cost of new technologies Cost of adaptation New costs for electricity
4	Climate change counter	Reduction of carbon emissions Subsidizing green energy Health Care Environmental taxation	The stock of atmospheric CO2 Temperature deviation	Melting ice Rising levels in the ocean Emissions reduction
5	Natural resources and ecosystem recovery	Quality of natural resources Biodiversity Microclimate and biological heritage	Resources price Natural resources restoration price	New technology research and development Tax on reforestation

Source: created by the authors based on their research

Research results and discussion

1. Green City concept – land and economy

Figure 2 illustrates a critical facet of the green urban paradigm, emphasizing the valuation of land use within the urbanization continuum. This analysis recognizes a plethora of socio-economic and market determinants that orchestrate the appraisal of potential land use costs. In scrutinizing urban and suburban land dynamics, this discourse homes in on pivotal factors that significantly influence the evolution of the green city concept. For analytical clarity, urban and peri-urban land allocations are categorized into quintessential segments: residential, agricultural, industrial, institutional, and green spaces. Beyond the aggregate valuation of real estate, this examination contemplates additional variables including land use regulations, maintenance obligations, and environmental liabilities, which collectively impact urban land management practices.

Land utilization and stewardship emerge as foundational elements of green urban economics, facilitating diverse agricultural productions, and supporting the sustenance of various industrial sectors through the judicious exploitation of natural resources. Expanding this perspective, land cover is systematically classified into distinct landscape archetypes such as grasslands, wetlands, forests, arable terrains, and mixed landscapes, among other terrestrial forms. This stratification aids in the comprehensive understanding of land resource management, underscoring the necessity for sustainable practices in nurturing the green city ethos, thereby enhancing urban resilience and ecological balance.

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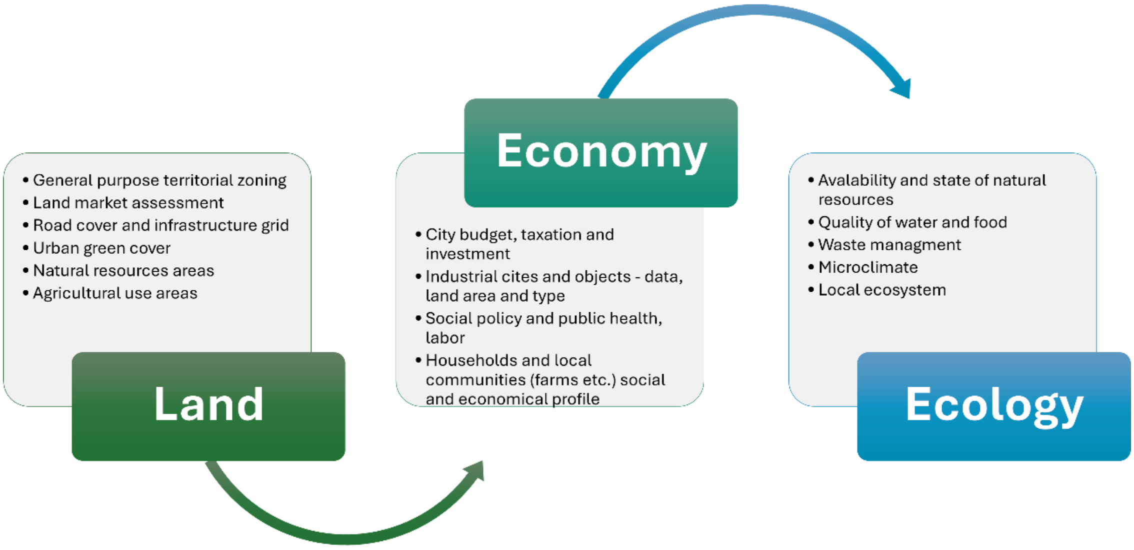

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Fig. 2. **Green city components – Land, Economy and Ecology**

Figure 3 elucidates the integral role of forest cover within the paradigm of the Green City economic model, proposing its recognition as a pivotal economic asset within economic analyses. This framework delineates urban forests under several classifications: as landed assets for potential development projects; as foundational elements of the raw material inventory; and as central recreational zones within urban landscapes. However, this categorization potentially underrepresents the multifaceted contributions of forest and green spaces to urban ecosystems. A more expansive analysis is warranted, one that encompasses the strategic integration of long-term economic and environmental planning for urban and surrounding regions.

Forests represent critical ecosystems that underpin biodiversity and offer essential ecosystem services vital for sustaining life on Earth. They engender extensive biosystems, playing a pivotal role in the ecological and atmospheric equilibrium. The exploration of forest cover's influence on urban development is of paramount importance, particularly in an era where urbanization trends have culminated in a significant portion of the global population residing within city confines. The ramifications of alterations in green cover manifest conspicuously in everyday urban life, influencing climate regulation, air quality, and public health.

Urban land use extends beyond residential and commercial development, incorporating agricultural activities and the utilization of natural resources to support various industrial sectors. Land cover is broadly categorized into ecosystems such as grasslands, wetlands, forests, arable lands, mixed landscapes, among others, each contributing uniquely to the urban environmental matrix. While forests may not be directly quantified within gross domestic product (GDP) calculations or mainstream economic development strategies, their intrinsic value to the economy, through ecosystem services like carbon sequestration, water regulation, and biodiversity conservation, cannot be overstated. Acknowledging and integrating the ecological and economic functions of forests into urban planning and economic modelling is essential for fostering sustainable urban growth and enhancing the resilience of urban ecosystems against environmental challenges. Figure 4 showcases the Green City Information City model, divided into software modules, functions, and data types.

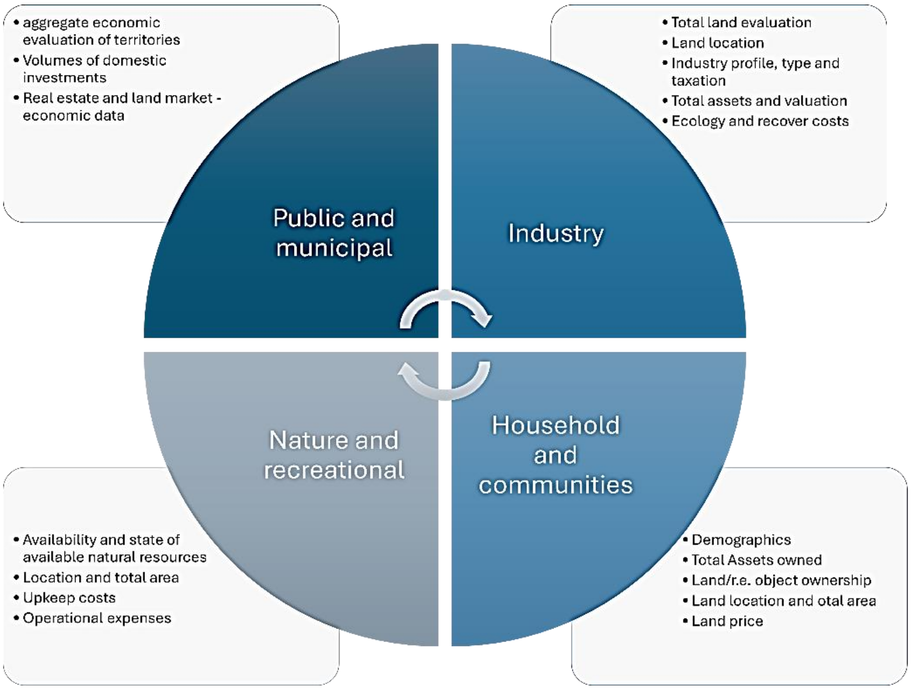

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Fig. 3. **Land areas' economic development under the Green City concept**

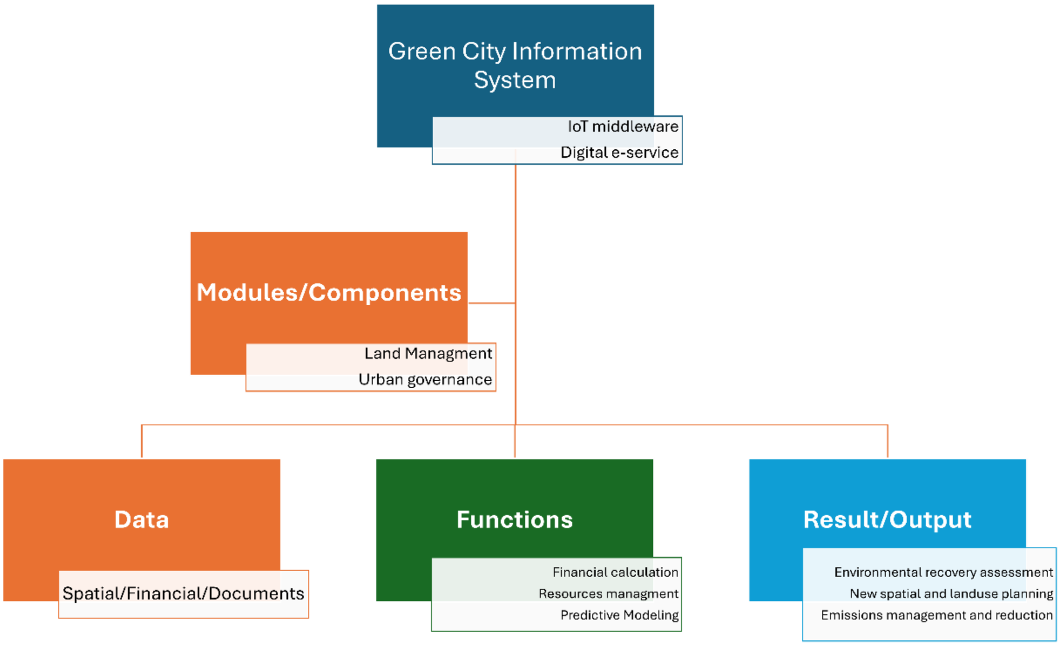

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Fig. 4. **Green city information system model**

2. Green City Service Model

The nexus between urban development and environmental transformation is undeniably profound, with urban expansion - encompassing the growth of city perimeters and suburban vicinities - exerting considerable influence on ecological systems. This influence manifests through the densification of infrastructure, such as road networks, and the spatial allocation of industrial entities, leading to escalated emissions of pollutants and degradation of environmental quality. Such anthropogenic pressures adversely impact public health, biodiversity, soil integrity, and atmospheric conditions. Additionally, the urbanization trajectory significantly affects aquatic ecosystems, including the health of rivers and reservoirs.

Table 3 delineates a comprehensive economic model for quantifying the ecological and economic dimensions of urbanization. This model facilitates the precise calculation of costs, expenditures, and losses associated with the exploitation of natural resources, alongside the financial gains derived from the commercialization of such resources. The parameters encapsulated within this model include the total valuation of the ecological system or territory, quantifiable losses of natural resources, financial inputs toward restoration or maintenance efforts, tax implications, valuation of natural and raw materials, export volumes of raw materials, leasing fees, contributions to oxygen production, aggregate real estate or land value, cost implications of resource exploitation or depletion, post-depletion land value, net profits from raw material or finished product sales, restoration taxation, overall economic returns from the territory, and carbon dioxide emission volumes.

Table 3

Green City Information System list of major system data, functions, and output

Information System Module	Data types and units of measurements	Functions	Output
Land management	Interest rate, % Object location, spatial Object profile, mix. Object valuation, $ Natural resource price, $ Natural resource profile, mix. Harmful emission, tons per type per year	Property tax calculation The total value of real estate/land Profit from the sale of raw materials or finished products by the enterprise	Land lease payment for the use of an area with available natural resources The total value of the land after the loss of natural resource
Urban governance – economy, social and financial	City budget and expenditures (volume), $ per year Volume of investments by type of economic activity, $ per year Profit of companies by type of economic activity, $ per year City GDP growth rate, %	Green Tax Calculation Cost of land and resources restoration	Social (public) benefit from the presence of a certain type of territory within the city or adjacent territories Cumulative economic benefits from the land/object
Ecology and sustainable development	Climate and weather monitoring data, numerical State and availability of natural resources, mix. Price of natural resources, $ (per ha.)	The cost of untreated, clean natural resources before they are used Economic value of the territory of a forest or nature reserve Investment in recovery or support req.	City Waste Management Program Cumulative losses/gains of natural resource The cost of conversion for the exploitation or destruction of a natural resource

Source: created by the authors based on their research

This integrative economic model provides a robust framework for assessing the fiscal and ecological footprint of urban development on natural resources, enabling calculations on a per-area or temporal basis, and facilitating a comprehensive understanding of the economic viability of resource utilization strategies. Through such analytical rigor, it becomes possible to harmonize urban expansion with environmental stewardship, thereby fostering sustainable development paradigms that acknowledge the intrinsic value of ecological assets within the urban planning discourse.

The use of land areas, forests, lands occupied by agricultural production, life, and urban development - all these factors have a significant impact on the environmental situation in the region. Therefore, it is always necessary to take into account and plan the economic consequences of such events and calculate options for the development of the use of amalgamated territorial communities, both in the country as a whole and around large cities and adjacent and suburban areas. As presented above, the intensive use of

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land resources and the construction of new industrial and residential facilities entails significant environmental consequences. The author notes the expediency of developing an integrated approach to assessing the cost of environmental losses and environmental costs in the context of territorial and economic planning by city authorities and amalgamated territorial community councils. It is necessary to develop a new legislative and legal framework for economic and legal levers of control over the impact on the environment in cities and settlements. Environmental programs in prominent urban centres include the development of wastewater treatment systems at the municipal level, wastewater treatment and integrated waste recycling, reclamation of agricultural land, and new urban development plans taking into account the concept of sustainable development.

3. Green City IoT-based Information System

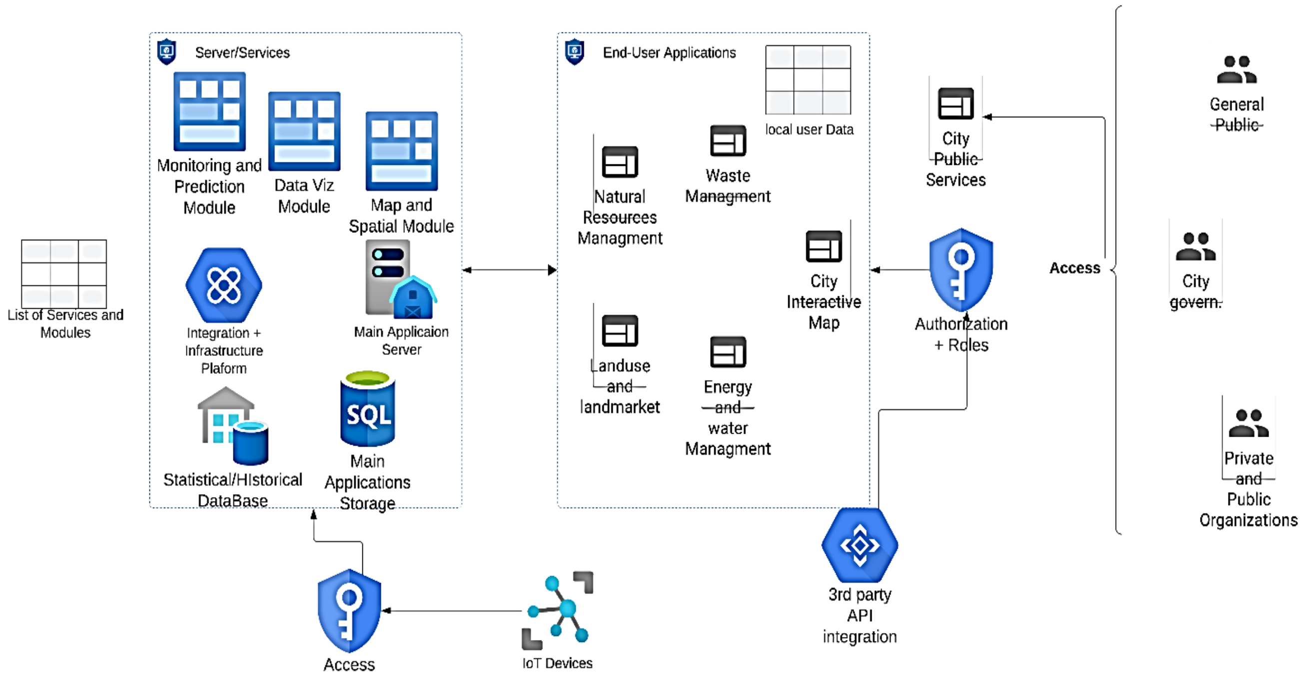

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Fig. 5. **Green City Information System Concept**

Green City Information System (Figure 5) can be used for urban governance, especially city management, resource planning, and general city surveillance. Green City's software model highlights horizontal IoT-based system architecture with several layers – software systems and servers, applications, integration points, and user roles. In the future, this System can be used to develop an initial porotype or implement integration software modules into existing smart city management software suits. The valuation of aquatic resources within urban environments poses a complex challenge, encompassing the assessment of their influence on real estate valuations, environmental quality, biodiversity, and urban aesthetics. This necessitates the compilation of comprehensive catalogues delineating various urban water zones, alongside the proposition of strategic frameworks for their management, enhancement, and ecological integration. Such evaluations must consider the dynamics of hydrological replenishment, including precipitation patterns and their implications for urban water sustainability.

Future research endeavours must prioritize the examination of urban water bodies, scrutinizing the transformations induced by urban activities and expansion. A critical area of inquiry involves the correlation between the proximity of real estate to aquatic environments and the consequent trends in property values. This investigation should extend to the exploration of how these relationships vary across cities of differing sizes-from small towns to metropolises-and how access to water bodies influences urban planning and development trajectories.

A comparative analysis of cities from diverse geographical contexts, such as Kyiv, Dnipro, and Odesa in Ukraine, and Warsaw and Gdansk in Poland, would illuminate the economic and environmental impacts of urban water bodies. Furthermore, cities like Amsterdam in the Netherlands and Bruges in Belgium, renowned for their rich integration of natural water resources within urban fabrics, offer unique case studies for exploring the symbiosis between urban development and aquatic ecosystems.

The development of a green city economic growth plan entails a sequential approach:

1) Implement territorial zoning to categorize regions into suburban areas, transitional zones around cities, urban development types, and economic profiles, including metropolitan areas, based on their economic characteristics.
2) Forge a holistic model of the urban social fabric to evaluate the effects of territorial expansion on population well-being and living standards, employing socio-economic models to dissect the impacts of urbanization on household economic and social dynamics.
3) Execute ecological and economic projections to gauge the repercussions of urbanization on the economic vitality of specific areas, the broader metropolis, and the regional ecosystem, aiming to quantify the aggregate ecological worth of natural resources or ecosystems implicated in urbanization.
4) Articulate a set of guidelines for identifying emerging spatial economic and investment hubs, alongside an environmental and economic appraisal of potential risks stemming from ecological alterations.
5) Design an overarching strategy for green urban economic development, leveraging information system models for its implementation and operationalization.

This structured methodology underscores the integration of environmental stewardship with urban economic planning, advocating for a sustainable urban development paradigm that harmonizes economic growth with ecological preservation.

The function of determining the total ecological value of a natural resource or ecosystem related to the urbanization process

$$TECu = f(C) = \int_0^n f(C)dt \quad (1)$$

Where:

C - the total economic value of natural resources or ecosystems affected by the urbanization process;

n - time for complete restoration of the state of the ecosystem (up to a certain time period);

t - time to restore the ecosystem or natural resources.

Formulae 1 shows the mathematical representation of the data we have shown in Fig. 5 on the economic information model of costs associated with green spaces and Table 3 on economic data for the economic information model of costs associated with green spaces in the context of urbanization development process. The total economic value of natural resources or ecosystems affected by the urbanization process (C) can be calculated based on the social costs of ecosystem and/or resource (per type), cost for resource restoration, cost of resources lost, green tax rate, and several other components. The function will be further developed, evaluated, and presented in future research work.

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Conclusions, proposals, recommendations

Within the ambit of urbanization and its attendant ecological impacts, a sophisticated ecological and economic framework has been conceptualized to elucidate the economic ramifications of land utilization and urban development. This framework pioneers the integration of sustainable development principles with rational land use practices, underpinning the genesis of the "green city" concept. Central to this innovative model is a meticulously curated classification of analytical tools and methodologies designed to quantify the economic costs engendered by ecological considerations. These methodologies serve as the foundational pillars for the "green city" paradigm, harmonizing economic development objectives with environmental stewardship. This integrative approach underscores the imperative of sustainable urban planning, advocating for a balanced coexistence between urban expansion and the preservation of ecological integrity. Through the application of this model, urban development strategies can be reoriented towards sustainability, ensuring that economic growth and environmental conservation are pursued in tandem for the betterment of urban ecosystems and their inhabitants.

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