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Forecasting land use and land cover change as a tool for optimising adaptation to climate change: Examples of selected Second-Tier Cities of the V4 Group

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Abstract. Second-tier cities are an important element in the socio-economic development of each country, including V4 countries. The result is a dynamic change in land use/cover patterns. The article analyses the possibility of using Markov chains to predict changes in land use. The results show that it is possible to use the Markov chains method in proper decision-making in land-use policy, which is combined with the stimulation of sustainable land use. The research results show that Markov chains can be an important tool to guide cities' climate policies and build their capacity to adapt to climate change.

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1. Introduction

Climate change is a major environmental issue. Surveys conducted in individual countries, as well as at the European Union (EU) level, clearly demonstrate that the public considers climate change a key threat to the survival of society and the economy. This opinion is shared by 62% of Danes (DK), 61% of Swedes (SE) and 60% of Finns (FI), with the EU-28 average of 53%. For 49% of Norwegians (NO), climate change is the biggest challenge among the 14 policy issues, followed by health care (45%) and immigration and integration (35%), Among the Nordic members of the EU, 47% of Danes, 50% of Swedes and 33% of Finns believe that climate change is a major threat to the whole world (EU-28 average: 23%) (cf. Helbling, 2020). In Poland, awareness of climate change is steadily increasing year on year. In 2020, compared to the 2018 survey, the share of responses where climate change is identified as a serious issue increased by 30 percentage points (2018 – 39%, 2020 – 68%). Seven out of ten Polish residents consider climate change a very serious problem, and one in four believe it is somewhat important. The Polish respondents believe that the state of the environment depends mostly on human behaviour patterns (69%) (Ministry of Climate and Environment, 2020).

The summer of 2022 saw the highest average temperatures on record in Europe. The extreme heat also increased the risk of drought. In many areas across Western Europe and in parts of Eastern Europe, August 2022 was significantly drier than average, although many parts of Europe had already experienced below-average rainfall for several years in a row. This uncertainty and climate variability means that, by the end of August 2022, almost two-thirds of Europe was at risk of a drought referred to as probably "the worst in at least 500 years" as described in a recent assessment by the European Commission's Joint Research Centre (EEA, 2023).

The dynamics of climate change are generated largely by social and economic activities in urban areas. Cities are simultaneously the key drivers and the main recipients of these changes. A report by the European Environment Agency (2018) pointed out that the most important problems resulting from climate change for European cities are pollution and extreme temperatures. Although human–environment interactions are increasingly better identified in cities, there is still a need to take a comprehensive look at how they work, especially regarding the use of space and its development through the lens of the climate crisis.

This article discusses the scale and scope of changes in the use and spatial development of selected European cities in the context of the climate crisis and the need to build climate-neutral cities and stimulate the climate policy of contemporary cities. Seeing space as a good that is free but not a common one leads to its appropriation and substantial restructuring, i.e. something we are witnessing today. The development of urbanised areas has always clashed with the principles of sustainability. Jenks and Jones (2010) believe that when assessing the spatial form of a city from the point of view of sustainability, one should, first and foremost, take into account land use as spatial planning does not sufficiently address environmental issues or future costs. In addition, while spatial chaos intensifies climate change, it also hinders necessary adaptation measures (Rzeńca & Sobol, 2020). The effects of climate change are local by nature, and a place-based approach and the 'think globally, act locally' (United Nations, 1992) principle must be followed to truly resolve the problems that they trigger. The legitimacy of evidence-based policy in urban development planning is crucial for the day-to-day functioning of a city in the face of local environmental threats and how it mitigates and adapts to climate change. As a result, cities are key arenas for pursuing active climate policy through territorially oriented concrete actions (Angelo & Wachsmuth, 2020). In terms of spatial planning, this means compact development, limiting urban sprawl and a high level of environmental protection and quality, including an adequate share of green and open spaces in and around cities.

Strengthening inclusive and sustainable urbanisation is strongly linked to The Sustainable Development Goals (SDG) of United Nations (UN) Goal 11: Sustainable cities and communities. It points towards making cities and human settlements safe, stable, sustainable, and inclusive. The EU's European Green Deal strategy is a landmark document for the development policies of EU countries, as well as their cities, in the coming years. Its main objective is to "set Europe on a path of transformation towards a climate-neutral, fair and prosperous society with a modern, resource-efficient and competitive economy." This expanded objective is a guideline for cities, and its local character is highlighted by the Green Deal Going Local initiative. For the EU, climate policy is a way to achieve three main objectives: reducing greenhouse gas emissions, increasing energy efficiency and security, and adapting to climate change. In addition, the Leipzig Charter for Sustainable European Cities, the Amsterdam Pact and two new EU documents, the EU Territorial Agenda 2030 and the New Leipzig Charter, delineate the direction for urban development and the framework for a 'new' urban policy directed 'inwards', with people and places, sustainability and climate change as the focal points. The city is designed around the demand for energy efficiency and ideas promoting sustainable transport and mobility, sustainable urban biodiversity, urban planning and urban design, and sustainable buildings.

The mainstream research trends of the green economy, smart city 5.0, the circular economy and urban resilience correspond with policy statements and urban policy guidelines. They highlight the role of natural resources and environmental circumstances in development (Loiseau et al., 2016; Röhr, 2011), as well as the relationship between the socio-economic system and ecosystems (Millani, 2000). From the perspective of contemporary cities and their policies, we are therefore talking about reducing the demand for resources (including space) and energy, as well as diminishing environmental burdens (Millani, 2000; Brand, 2012). The idea of urban metabolism, a system co-created by many elements, sub-systems, and systems between which there are strong interactions, marks a departure from the technocratic and technical approach to the city. It indicates that the city is not a metaphor for a collection of different elements but a 'living' system of complex and interdependent energy, material and ecological processes in which matter and energy flow. Space is a key element of this system, especially open spaces, unmanaged green spaces, and urban forests. The research results bear this out into the value of green spaces, the proximity of green spaces, and the role of formal and informal green spaces in the city (Czembrowski et al., 2016; Kronenberg et al., 2020, 2024; Sikorska et al., 2023).

The concept of ecosystem-based management (EBM) (McLeod & Leslie, 2009), which emphasises the role of a holistic approach to managing socio-economic-ecological systems, is coming up against the complex, multi-threaded management of complex urban areas. The idea of a circular economy, where the industrial (production) dimension, including technology, is enriched with biological, social, and organisational processes (Andersen, 2007; McDonough & Braungart, 2013; Webster et al., 2013; Tse et al., 2015), is also becoming an important element of urban development. In relation to cities, the circular economy requires holistic thinking about urban natural resources and anthropogenic and environmental flows. Particularly desirable are nature-based solutions (NBS) that stimulate the development of circular cities, close the circuits of flows of raw materials, materials, and products, and benefit from natural processes (Langergraber et al., 2020). This approach coincides with the concept of the green city, a city that is more citizen-friendly. Compact development remains crucial for supporting economies of scale, minimizing unregulated intrusion in ecosystems, and facilitating other sustainable urban development measures such as creating cities of short distances, sustainable neighbourhood planning, and 15-minute and 20-minute cities. Well-designed and well-managed compact cities with equitable distribution of infrastructure and services, mixed uses, walkable access to open and green spaces, and support for vulnerable residents during adverse events (e.g. economic support packages and the delivery of food and basic services) are safe and resilient to pandemics (United Nation, 2022). These theories are relevant in the context of depopulation and urban aging processes (Langner & Endlicher, 2007; Śleszyński, 2016; Śleszyński & Kukołowicz, 2021; Aurambout et al., 2021).

Climate change and its consequences affect all cities, but the scale and extent of changes are determined by local factors and the city's development trajectory. Second-tier cities, little discussed in the literature, are a special case study. They are the driving force behind the development of regions and nation-states. There is no clear typology of second-tier cities since, according to the approach adopted by the European Spatial Planning Observation Network ESPON (ESPON, 2012), in Europe alone, one might apply a multi-criteria approach to this research and analytic topic. For analysis that goes beyond the borders of a single continent, the approach should be standardised depending on the spatial dimension of the comparisons. For the approach presented in this article, we used the second-tier city classification presented by ESPON.

Notwithstanding the approach presented in the literature that points to the economic relevance of second-tier cities in regional development and their function as integrators in creating territorial cohesion (Evans, 2015; Cardoso & Meijers, 2017), their important role in stimulating internal development should also be mentioned. Appropriate spatial policies related to spatial development and transformation linked with changing the dominant functions of second-tier cities produce changes in land use/cover within administrative boundaries. Such activities transform land use patterns and land cover structures (LULC). Human activities impact terrestrial sinks through land use, land-use change and forestry (LULUCF) activities. Consequently, the exchange of CO_2 (the carbon cycle) between the terrestrial biosphere system and the atmosphere is altered. Human activities affect changes in carbon stocks between the carbon pools of the terrestrial ecosystem and between the terrestrial ecosystem and the atmosphere. Mitigation can be achieved through activities in the LULUCF sector that increase the removal of greenhouse gases (GHGs) from the atmosphere or decrease emissions by halting the loss of carbon stocks.

Second-tier cities are entities with high development dynamics, which poses challenges for local authorities in the sphere of spatial planning. Indeed, the dynamics of development should not restrict the potential of biologically active areas, which, in the context of climate change, determine the appropriate performance of other policies carried out in second-tier cities (Marais & Nel, 2019). These measures are intended to prevent urban sprawl, particularly within the administrative borders of cities. The problem is also noted in scientific publications relating to second-tier cities, which dynamically transform non-built-up areas into low-value space for the provision of ecosystem services in cities (Roberts, 2014; 2019).

The extensive literature related to analytical approaches to land use change forecasting makes reference to many scientific disciplines. Indeed, it relates in particular to the analysis of spatial information systems and remote sensing (Roy et al., 2015; Fallati et al., 2017; Mas et al., 2017; Vasenev et al., 2019; Atay Kaya & Kut Görgün, 2020) or the impact of LULC change on socio-economic contexts (Desalegn et al., 2014; Xystrakis et al., 2017). There are also references to the increasingly broader topic of ecosystem services, which are an important element in cities' socio-economic development (Gomes et al., 2020; Bindajam et al., 2021). Ecosystem services are an important element in urban development, influencing the well-being of residents and the real estate market (Pietrzyk-Kaszyńska et al., 2017; Sikorska et al., 2020).

The main goal of the study is to identify the scale and scope of changes in land use and to analyse changes in LULC in four second-tier cities of the Visegrad Group: Brno, Košice, Lodz, and Miskolc, from 2006 to 2018. Satellite remote sensing, GIS, and Markov modelling were used to investigate the stochastic nature of LULC change data, and to predict the stability of future land development in these cities.

2. Data and methods

2.1. Classification of the data used in the analysis

For the LULC-related analyses, data from the Urban Atlas (UA) collection were used. Vector data are available from the Copernicus Land Monitoring Service (CLMS), which is managed by the European Environment Agency (EEA). With the UA data, it is possible to track changes in LULC for Functional Urban Areas (FUAs), which, depending on the year of data acquisition, include functional areas with 100,000 inhabitants (2006 data) and functional areas with 50,000 inhabitants, as of 2012. Vector data are currently available for three time points: 2006, 2012 and 2018. (Table 1)

The UA data were reviewed in terms of the typologies used, which influences their accuracy and usability in subsequent analysis. The UA databases were expanded with new typologies that allow for accurate land cover depiction within the FUA framework. Based on the spatial datasets, it was possible to divide them into four classes used in the analysis: residential, industrial, and service, infrastructure, and green areas. In the last case, both formal and informal green spaces were included into this group (Rupprecht & Byrne, 2014; Rupprecht et al., 2015; Feltynowski et al., 2018; Manyani et al.,

Table 1. Relationship between local landform and urban planning solutions.

	Urban Atlas 2006	Urban Atlas 2012	Urban Atlas 2018
FUA size	100,000 inhabitants	50,000 inhabitants	50,000 inhabitants
FUA number	319	785	788
Covering	EU27 in 2007	EU28 + EFTA countries + West Balkans + Turkey	EU27 in 2021 + EFTA countries + West Balkans + Turkey + UK

Source: own work based on Copernicus Land Monitoring Service metadata.

2021) (Table 2). Using classifications available within the UA framework allows for the explicit aggregation of sites that are then subject to analysis.

2.2. Study area

The spatial scope of the study comprised Central European countries brought together into the Visegrad Group (V4): the Czech Republic, Poland, Slovakia, and Hungary. The cities of Lodz in Poland, Brno in the Czech Republic, and Miskolc in Hungary were randomly selected. Kosice was chosen in Slovakia as it is the only second-tier city in the ESPON report (Table 3). Figure 1 shows the location of the cities chosen for the study.

Apart from their many common features, the cities have unique spatial organisation. The shaping of the urban centres reflects the local history and traditions, as well as social, political, and economic changes. These circumstances vary in space. The cities fit into urbanisation trends as they exemplify the effects of dynamic changes triggered by the industrial revolution in the 19th century, followed by a second wave of accelerated urbanisation since the mid-20th century. For these post-communist cities, the post-war political reality, and the impact of the centrally planned economy model imposed

Table 2. Data classification

UA2006	UA2012	UA2018
Residential areas		
Continuous urban fabric (S.L.: > 80%)	Continuous urban fabric (S.L.: > 80%)	Continuous urban fabric (S.L.: > 80%)
Discontinuous dense urban fabric (S.L.: 50% - 80%)	Discontinuous dense urban fabric (S.L.: 50% - 80%)	Discontinuous dense urban fabric (S.L.: 50% - 80%)
Discontinuous medium-density urban fabric (S.L.: 30% - 50%)	Discontinuous low-density urban fabric (S.L.: 10% - 30%)	Discontinuous low-density urban fabric (S.L.: 10% - 30%)
Discontinuous low-density urban fabric (S.L.: 10% - 30%)	Discontinuous medium-density urban fabric (S.L.: 30% - 50%)	Discontinuous medium-density urban fabric (S.L.: 30% - 50%)
Discontinuous very low-density urban fabric (S.L.: < 10%)	Discontinuous very low-density urban fabric (S.L.: < 10%)	Discontinuous very low-density urban fabric (S.L.: < 10%)
Green spaces		
Agricultural, semi-natural areas, wetlands	Arable land (annual crops)	Arable land (annual crops)
Forests	Forests	Forests
Green urban areas	Green urban areas	Green urban areas
Isolated structures	Herbaceous vegetation associations (natural grassland, moors...)	Herbaceous vegetation associations (natural grassland, moors...)
Land without current use	Isolated structures	Isolated structures
Sports and leisure facilities	Land without current use	Land without current use
Water	Pastures	Pastures
	Sports and leisure facilities	Sports and leisure facilities
	Water	Water
	Wetlands	Wetlands
Industrial and service areas		
Construction sites	Construction sites	Construction sites
Industrial, commercial, public, military and private units	Industrial, commercial, public, military and private units	Industrial, commercial, public, military and private units
Mineral extraction and dump sites	Mineral extraction and dump sites	Mineral extraction and dump sites
Infrastructure		
Airports	Airports	Airports
Other roads and associated land	Other roads and associated land	Other roads and associated land
Railways and associated land	Railways and associated land	Railways and associated land
		Fast transit roads and associated land

Source: own work based on Copernicus Land Monitoring Service metadata

Table 3. Second-tier V4 cities

Czech Republic	Poland	Slovakia	Hungary
Ostrava, Brno, Plzen, Hradec Kralove - Pardubice	Katowice-Zory, Krakow, Gdansk, Wroclaw, Lodz, Poznan, Kielce, Wloclawek, Lublin Bydgoszcz, Szczecin	Kosice	Debrecen, Miskolc, Szeged, Pecs, Gyor

Source: own work based on ESPON, 2012

Fig. 1. V4 second-tier cities in the research
Source: own work based on Eurostat vector data

by the Soviet Union largely dictated the scope of spatial transformation. Political decisions, which often went against location theory, for example, had consequences for the use and development of urban space and were reflected in the physiognomy and landscape of cities of the Eastern Bloc. Making urban development dependent on industry in the post-war period can be attributed more to the influence of socialist ideology rather than an inherent connection between industrialization and urbanization. This approach aimed to create a model of a communist city, emphasizing the development of robust industrial sectors.

A city's permanent status in the settlement hierarchy is almost inevitably linked to the many different functions that it performs (Gottmann, 1974). In contrast, when one specialised activity prevails, as is the case of the mono-functional cities in question, their decline tends to lead to the cumulative causation described by Myrdal (1957). In 1989, the post-communist economic transformation began. The transformation and growth of the four cities were rooted in significant political and economic changes. These changes were driven by the development of the service sector and a substantial decline in the proportion of industrial activities. However, the transformations and the consequences did not occur evenly. While some local economies were rapid and successful, others experienced a painful time (Bucek, 2002). All underwent deep restructuring and sought alternative forms of development. They were characterised by different dynamics of transformation and institutional conditions (e.g., legislative solutions, availability of resources, political set-up) (Blam et al., 2016). Economic and social conditions determined spatial policy, and suburbanisation and revitalisation determined the trajectory of spatial development.

Table 4. Industrial past of the V4 cities covered by the analysis

Brno	Lodz	Kosice	Miskolc
The weaving industry developed in the 18th century. Intense industrial development and specialisation earned Brno the name 'the Moravian Manchester'.	The dynamic development of the textile industry in the 19th century led to the rapid growth of the city area and population.	Kosice is referred to as the "iron or steel heart" of Slovakia because the city hosts the biggest steelworks in Slovakia.	Iron metallurgy, machine and rolling stock manufacturing factories, and Hungary's largest pulp and paper companies led to the city's growth.

Source: own work

2.3. The Markov chain method

Markov chains are one of the most important stochastic models. They can be used to greatly simplify processes that satisfy the Markov property where the future state of a stochastic variable depends only on its current state. This means that knowledge of the previous history of the process will not improve future predictions. Thus, we can significantly reduce the amount of data that needs to be considered. Markov chains often specify both time and a finite set of states as discrete values. Transitions between states are recorded as a transition matrix, which records the probability of moving from one state to another over a specified period.

Markov chains have huge applications in various fields, and many examples can be found in the literature, e.g., Clark (1965) on urban housing markets, Harris (1968) on land use, and Marble (1967) on travel patterns. Collins (1972) used Markov chains in forecasting industrial migration, while Berry (1971) outlined a short-term model of neighbourhood turnover. Bourne (1976) suggested this method to monitor changes in Toronto's spatial structure between 1952 and 1962. Weng (2002) combined the capabilities of geographic information systems and remote sensing with a Markov chain model to predict the possible consequences of rapid urbanisation and industrialisation. Muller and Middleton (1994) used LULC data from five different points in time between 1935 and 1981 to estimate a three-state Markov chain to predict the consequences of the urban development in the Niagara region of Ontario, Canada. Levinson and Chen (2005) presented a Markov chain model of LULC change in the Twin Cities region using historical data, while Chu (2020) used one to forecast future land use change.

The Markov chain is often applied to simulate various complex processes, one being LULC change. This model is mainly used to determine the trend of change between different land use categories using a transition probability matrix.

The Markov chain is a stochastic process $\{X_t; t \in T\}$, where T is a discrete index set that describes the probabilities of transitioning from one state to another. It is characterised by the property that the value of the process X_{t+1} at time t+1 depends only on its value X_t at time t. The Markov property can be expressed mathematically as

$$P(X_{t+1} = j | X_1 = i_1, X_2 = i_2, \cdots, X_t = i) = P(X_{t+1} = j | X_t = i)$$

for every t∈T and for all sequences $i_1, i_2, \dots, i, j$.

In practice, X_t represents the state of some system at time t. The set of all possible states is called the state space of the process, and we denote it by S. The $p_{ij}=P(X_{t+1}=j|Xt=i)$ denotes the one-step transitional probability, which gives the probability that the process will transition from state i to state j in one time period.

A Markov chain with n states can be characterized by its transition probability matrix P dimension nxn, expressed below as

$$P = \begin{bmatrix} p_{11} & \cdots & p_{1n} \\ \vdots & \ddots & \vdots \\ p_{n1} & \cdots & p_{nn} \end{bmatrix}, \qquad (1)$$

where $0 \le p_{ij} \le 1$ for all $i,j=1,2, \dots, n$, and $\sum_{j=1}^{n} =_1 p_{i,j}$, $i=1,2, \dots, n$.

An important step in the Markov model is to obtain the primary matrix P_0 and the transition probability matrix P. Then the Markov forecast model can be described as follows

$$P_n = P_{n-1} \cdot P = P_0 \cdot P^n, \qquad (2)$$

where P_n is the unconditional probability of the system's state at any time n, P^n denotes the n-th power of P, and P_0 is the primary matrix.

Throughout the paper, we are dealing with a random transition count matrix M, which is defined in the usual way as

$$\mathrm{M} = \begin{bmatrix} \mathrm{m}_{11} & \cdots & \mathrm{m}_{1n} \\ \vdots & \ddots & \vdots \\ \mathrm{m}_{n1} & \cdots & \mathrm{m}_{nn} \end{bmatrix}, \qquad (3)$$

where m_{ij} denotes the number of transitions from state i to state j, where i, j∈S.

3. Results

3.1. Results of the classification and analysis of land use and land cover

The classification results of the processed images from 2006, 2012, and 2018 are shown in Figure 2. In all cities in the three analysed periods, the area of green areas is the largest, with 80.57% in Miskolc, 76.06% in Kosice, 62.86% in Brno, and 57.69% in Lodz. Infrastructure occupies the smallest area.

The data allows us to calculate the percentage changes in LULC in each city in the periods 2006-2012 and 2012-2018 (Fig. 3 and 4). The graphs

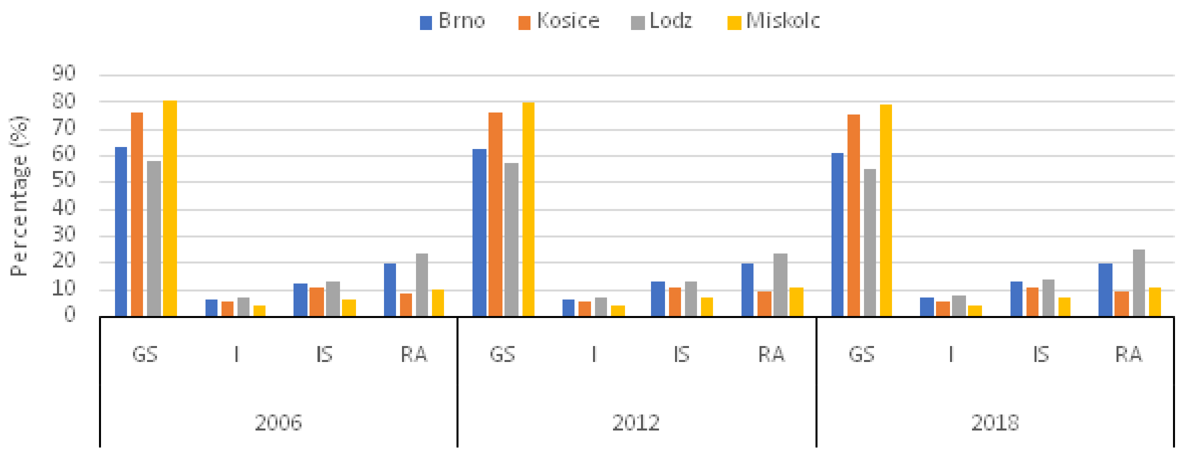

Fig. 2. Land use/cover in 2006, 2012, and 2018 for Brno, Kosice, Lodz, and Miskolc (%)
Source: own elaboration

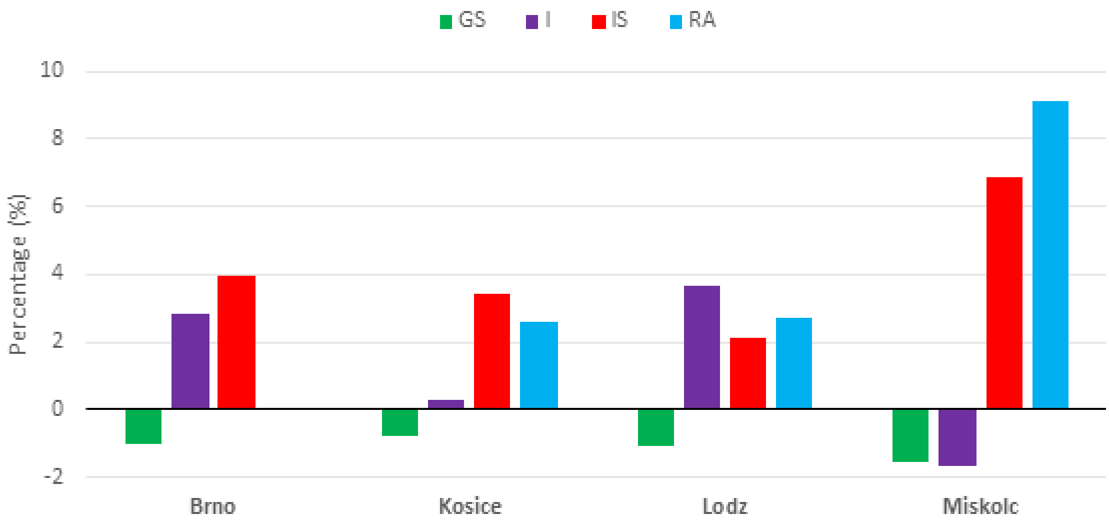

Fig. 3. Land use/cover changes from 2006 to 2012 (area %)

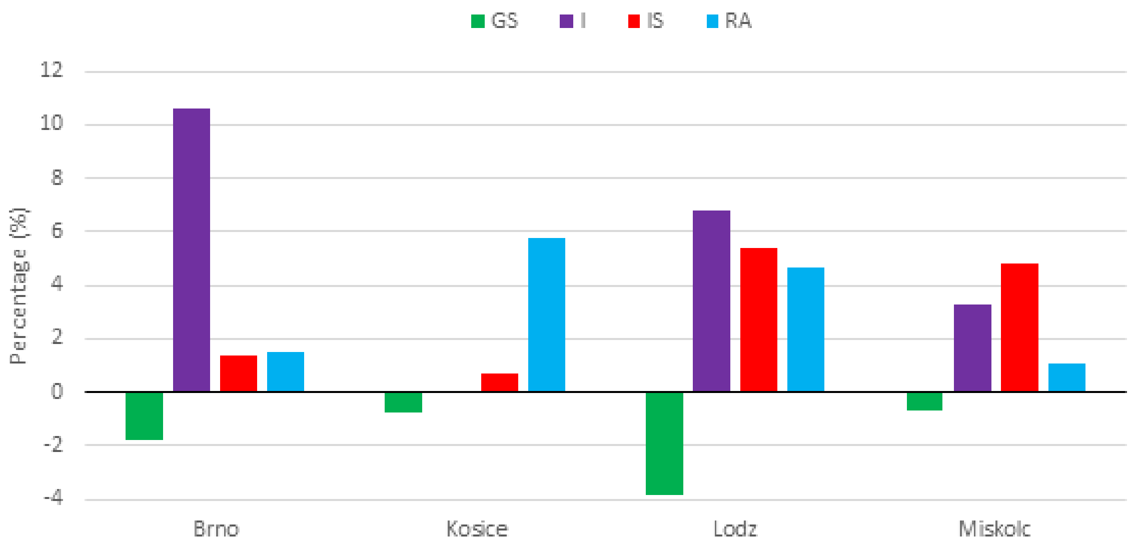

Fig. 4. Land use/cover changes from 2012 to 2018 (area %)

show detailed changes, i.e., an increase and decrease in the area of particular urban LULC categories. The changes in land use are obvious in these periods.

The main characteristics of land-use change from 2006 to 2012 show that industry, services, and residential areas increased, while green spaces decreased to some degree. While infrastructure increased in Brno, Kosice, and Lodz, it decreased in Miskolc.

The LULC changes between 2012 and 2018 are characterized by a large increase in infrastructure in Brno of around 11%. Other land use types, such as green spaces, decreased slightly. The largest decrease (around 4%) was in Lodz.

Table 5. Markov probability transition matrices of land use and land cover for 2006-2012, 2012-2018

Brno	**Transition Years**	**GS**	**I**	**IS**	**RA**
GS	2006-2012	0.9826	0.0024	0.0124	0.0026
	2012-2018	0.9798	0.0104	0.0059	0.0038
I	2006-2012	0.0008	0.9981	0.0005	0.0006
	2012-2018	0.0000	0.9995	0.0005	0.0000
IS	2006-2012	0.0117	0.0023	0.9738	0.0122
	2012-2018	0.0118	0.0002	0.9833	0.0047
RA	2006-2012	0.0155	0.0000	0.0002	0.9843
	2012-2018	0.0000	0.0000	0.0002	0.9998
Kosice	**Transition Years**	**GS**	**I**	**IS**	**RA**
GS	2006-2012	0.9912	0.0001	0.0070	0.0017
	2012-2018	0.9912	0.0000	0.0038	0.0050
I	2006-2012	0.0000	0.9989	0.0000	0.0011
	2012-2018	0.0000	1.0000	0.0000	0.0000
IS	2006-2012	0.0079	0.0012	0.9816	0.0094
	2012-2018	0.0073	0.0000	0.9800	0.0128
RA	2006-2012	0.0000	0.0000	0.0008	0.9992
	2012-2018	0.0000	0.0000	0.0000	1.0000
Lodz	**Transition Years**	**GS**	**I**	**IS**	**RA**
GS	2006-2012	0.9810	0.0021	0.0097	0.0072
	2012-2018	0.9595	0.0063	0.0163	0.0180
I	2006-2012	0.0007	0.9991	0.0001	0.0000
	2012-2018	0.0001	0.9932	0.0067	0.0000
IS	2006-2012	0.0095	0.0064	0.9719	0.0121
	2012-2018	0.0062	0.0100	0.9786	0.0052
RA	2006-2012	0.0019	0.0003	0.0003	0.9975
	2012-2018	0.0000	0.0004	0.0001	0.9995
Miskolc	**Transition Years**	**GS**	**I**	**IS**	**RA**
GS	2006-2012	0.9813	0.0004	0.0076	0.0107
	2012-2018	0.9921	0.0015	0.0049	0.0014
I	2006-2012	0.0263	0.9737	0.0000	0.0000
	2012-2018	0.0011	0.9989	0.0000	0.0000
IS	2006-2012	0.0288	0.0002	0.9663	0.0047
	2012-2018	0.0123	0.0000	0.9877	0.0000
RA	2006-2012	0.0000	0.0000	0.0000	1.0000
	2012-2018	0.0000	0.0000	0.0000	1.0000

Source: own work

3.2. Analysis of land use/cover change matrices

Describing how LULC changes in a given area, we obtain matrix M of the number of transitions between states, i.e., land categories S = {G, I, R, IS}, and matrix P of the probabilities of transitioning between them. A matrix of transition probabilities can be determined according to changes in land use area over a given time interval. This study used LLULC data from 2006, 2012 and 2018. Therefore, the time interval of transition probabilities between different land use categories is six years.

The available data made it possible to determine the transition probability matrix. The transition probabilities show the probability that each land use and land cover class in the study area will remain the same or change to a different one in the next period (i.e. 2006-2012, 2012-2018) (Table 5). This means that a given land use and land cover type can change from one category to any other category at any time, i.e., change is not unidirectional. The diagonal values in the transition probability matrix represent the probability that each land use category remains the same over a given period.

3.3. Predicting land use and land cover

To simulate land use areas in 2018, available LULC data from 2006 and 2012 were used. The land use in 2018 was simulated using the LULC data from 2012 as the starting point and the probability matrix of LULC change from 2006 to 2012.

The next step was to check the validity of the Markov chain model. A chi-square goodness of fit test was applied. This statistical test assesses whether a distribution adequately describes a set of observations by comparing the actual number of observations with the expected number (Weng, 2002). The statistic is calculated based on the following relationship:

$$\chi^2 = \frac{\sum_i \sum_k (O_{ik} - E_{ik})^2}{E_{ik}}, \qquad (4)$$

Table 6. χ^2 statistic value

City	χ^2 statistic
Brno	0.12
Kosice	0.04
Lodz	0.21
Miskolc	0.16

where O_{ik} is the observed and E_{ik} is the expected number of transition probability.

The simulated values of land use areas in 2018 were compared and checked with the actual values in 2018 using the chi-square statistic according to (4) to ensure suitability of the model.

With a critical region $\alpha=0.05$ and degrees of freedom n−1=3, the distribution of χ^2 is as follows:

$$\chi^2_{0.05}(3) = 7.815$$

Since $\chi^2<\chi_{0.05}{}^2$ (3) for each city, there is no significant difference between the simulated and actual values of land use change in the study area. The Markov chain model allows us to simulate the area of land use change in a reasonable and acceptable way, and overall accuracy is sufficient to assess land use change. Therefore, the Markov chain model can be used for land use prediction in Brno, Kosice, Lodz, and Miskolc.

Probability matrices for land use change in 2006-2012 and 2012-2018 (Table 5) were used to predict the size of future land use areas for different land use types in the study area. Namely, the average transition probability matrix to be used as the basic transition probability matrix M^0 was calculated according to the following equation:

$$M^0 = \frac{n_1 \cdot M_1 + n_2 \cdot M_2}{n_1 + n_2},$$

where M^0 is the primary matrix used for Markov chain model simulation, M_1 and M_2 are transition probability matrixes from 2006 to 2012 and from 2012 to 2018, respectively, and n_1 and n_2 represent a time interval of land-use data available (each is six years in this study).

Using a Markov chain model, the primary land use change probability matrix and the 2018 land use data treated as the initial land use status matrix allowed us to project land use area sizes for 2024, 2030, 2036 and 2042 based on a six-year time interval, (Fig. 5).

According to the projected scenario of LULC changes for 2024-2042, the general trends of future LULC changes in the considered cities suggest that the green areas will decrease, to the greatest extent in Lodz, while the land allocated to industry and services will steadily increase. Land allocated to infrastructure will increase in Brno and Lodz, while in Kosice and Miskolc, it will remain stable. As for residential land, the highest growth is forecast in Lodz, followed by Miskolc and Kosice, while in Brno, it will remain unchanged.

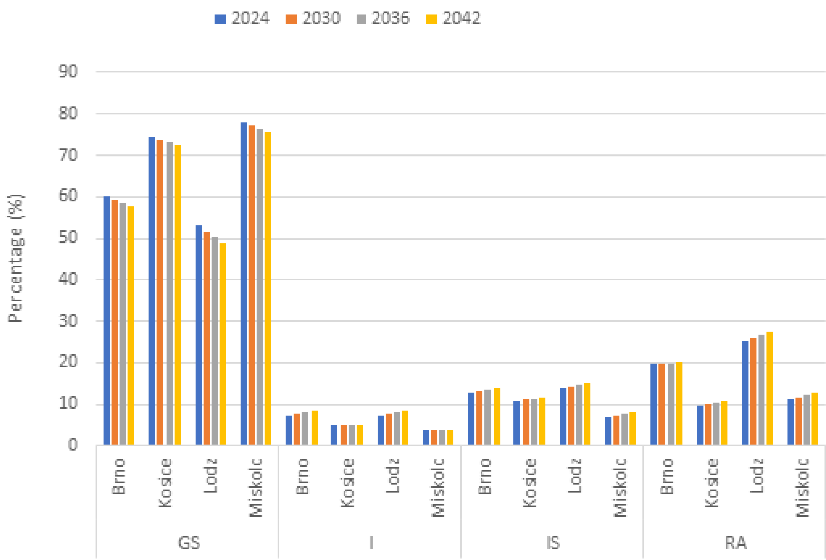

Fig. 5. Predicted land use/cover in 2024, 2030, 2036, and 2042 (%)

Table 7. Projected land use/cover changes in the 24-year period from 2018 to 2042 in km²

City\Types	GS	I	IS	RA
Brno	-7.51	3.61	2.55	1.36
Kosice	-5.54	0.08	1.86	3.60
Lodz	-16.63	3.72	4.20	8.71
Miskolc	-7.84	0.24	3.02	4.58

Analysing the graphs of the observed and projected areas of LULC changes from 2006 to 2042 shows that for Kosice and Miskolc, where the percentage of green areas was the highest, the percentage changes of green areas are very similar. In Brno and Lodz, the green areas were lower by about 20 percentage points in 2006 compared to the Kosice and Miskolc, while the projected percentage changes indicate the greatest reduction will be in Lodz. Regarding infrastructure areas, the projected percentage changes for Brno and Lodz are also very similar. The charts above highlight similarities between the cities.

The projected changes in land use in the 24 years from 2018 to 2042 show that the biggest changes can be expected in Lodz (Table 7). It will see the largest decrease in green areas and the largest increases in residential land, industry and services, and infrastructure.

4. Discussion

Land use is a dynamic element in the space of any city, and how it changes has been analysed extensively in the literature (Mölders, 2012; Nguyen, 2018; Rai, 2009). Analysis of LULC change patterns based on quantitative data serves to rationalise evidence-based policies (Feltynowski, 2018). This approach provides a solid foundation for optimising decisions over the long term, which are translated into the environmental health of the city and the mitigation of environmental risks and their effects. In addition, it facilitates the protection of unoccupied urban areas, making it possible to build a city that is resilient to climate change. The overarching goal of local authorities' spatial policy development is residents' quality of life (Ali et al., 2022; Ha et al., 2022; Stroud et al., 2022) and ensuring adequate conditions for them to accomplish basic biological, social and economic goals.

The research results clearly demonstrate the anthropogenic pressure and dynamics of LULC change towards economic or residential use at the expense of vacant land. The latest recommendations for shaping urban spaces suggest the need to put two ideas in place (European Commission, 2018): the compact city and, at the same time, the liveable city. The idea of the compact city indicates that it is better for cities to skilfully densify the existing urban fabric than to haphazardly expand development into previously uninvested neighbouring areas of cities.

The idea behind the liveable city concept is to shape a space in which residents will have easy access to all necessary services while maintaining a mixed-use development with a focus on green spaces. This requires redesigning spaces to be more flexible and resilient to shocks, disruptions or pandemics (Koprowska et al., 2020; Smiraglia et al., 2021; Yan et al., 2021). In addition, there is an urgent need to focus on strengthening integrated urban planning and territorial approaches that take into account interactions between urban, peri-urban and rural areas (United Nations, 2022). Taking care to reduce urban sprawl into unoccupied areas becomes the basis of cost ergonomics (Koprowska et al., 2020; Smiraglia et al., 2021; Yan et al., 2021). Current land use and projected changes have a substantial influence on the requirements for developing transportation and network infrastructure, including energy and heat systems. Consequently, these developments significantly impact the levels of low emissions and energy efficiency, thus playing a crucial role in the broader context of energy security. Appropriate spatial planning that relies on the densification of the building environment helps to increase infrastructure savings. This is because there is no need to add new elements into the urban space, but it suffices to modernize the existing structures and installations.

Any adaptation is local, especially in the context of spatial policy and urban planning decisions (Measham et al., 2011). To adequately plan for and adapt to these challenges, local governments must show leadership in three fundamental areas. Firstly, they need to go beyond climate change mitigation and put greater emphasis on mitigation and adaptation; secondly, they should push for reform at higher levels of government to make it possible to amend spatial planning regulations that currently hinder adaptation; and thirdly, to integrate adaptation activities into a broader range of activities, i.e., into urban policy. So far, climate change adaptation has not affected planners who oversee spatial planning as their activities have failed to include, e.g., the data collection phase. On the other hand, research shows that the institutional context (e.g., regulations and urban planning standards) for achieving climate change through local planning can be improved (Measham et al., 2011). However, the same socio-economic mechanisms produce different results depending on the circumstances in which they are launched (Sagan, 2000). Spatial planning is critical for building:

1. urban resilience, i.e., the ability of a system (city) to respond flexibly to the threats of climate change, not only to overcome them but also to improve the stability of the system and to be better prepared for future effects of climate change;
2. climate change adaptation, i.e., adapting to the unavoidable impacts of climate change to reduce or avoid the negative consequences of extreme meteorological and hydrological phenomena and long-term climate changes;
3. adaptive capacity, i.e., the capacity of the system (city) to adapt to the effects of climate change, which depends on the resources, i.e., potentials that can be used in the adaptation.

In each city covered by the study, the built environment is expanding while the green spaces that ensure biodiversity are shrinking. At the same time, undeveloped land (e.g., agricultural land and forests) is decreasing while the quality of the environment and urban residents' quality of life are measured by the amount and availability of green spaces for residents. This is particularly important in suburban areas within the administrative boundaries of cities (Budiyantini & Pratiwi, 2016; De Haas et al., 2021; Piorr et al., 2011). By caring for suburbs, a link can be created between green public spaces that allow ecological corridors to be created within cities. From the perspective of building biodiversity and, consequently, providing ecosystem services and building resilience, it is crucial to preserve green spaces of wild meadows, woodlands, and private and public green spaces in housing estates. Unmanaged, natural green space plays a key role.

In cities, the role of spatial planning in achieving high environmental quality, including the conservation of green space and the safeguarding of biologically active areas, has been underestimated (Rzeńca et al., 2021). Adequate accessibility and the quality and composition of green spaces can have an impact on the physical and mental health of residents and how they participate in the life of the city, the cost of heating and air-conditioning of buildings, property value, and the attractiveness of residential and business areas or crime rates (Bernardini & Irvine, 2007). The huge benefits offered by urban green spaces were the reason why the European Commission drafted a coherent document with recommendations for the implementation of the idea of green infrastructure (European Commission, 2013). The document emphasises the role of a 'strategically planned network of natural and semi-natural areas with other environmental features, designed and managed to deliver a wide range of ecosystem services (provision of food, raw materials, clean water, climate regulation, flood prevention, and recreation)' (European Commission, 2013). Blue-green infrastructure is one way of combating climate change, reducing temperature increases and the risk of localised flooding, and cleaning the air. Given the multiple functions of greenspace in urban spatial structure, especially in the context of inhabitants' quality of life, it is important that it is maintained in adequate quantities and in good condition (Beatley, 2000).

Like any organisation, the city operates in a VUCA environment, i.e., volatile, increasingly unpredictable, complex, and ambiguous (Bennett & Lemoine, 2014). The key actions that may help a city to find a place for itself in these conditions include coming to terms with obstacles posed by the environment, developing innovation, anticipating risks, and minimising long-term investments (Praveen, 2018). Integrity, diversity, efficiency and interdependence build a city's resilience and ability to adapt to the environment and the continuity of change (Hess, 2013; Drobniak, 2015).

A vision of cities proposed today could be described in three terms: sustainability, inclusiveness, and resilience. The sustainability of urban development is concerned with every sphere and function of a city. It also includes respect for and the rational use of available resources and finding substitutes. Resilience is linked with creating cities that are not susceptible to crises and can adapt to changing internal and external conditions (United Nations, 2016). For cities, having an effective climate policy is a development challenge. Climate policies should aim to reduce cities' impact on climate change and mitigate climate risks to the health and lives of residents that stem from climate change and the socio-economic development of cities (Ciscar Martinez et al., 2018). Priority should be given to a safe and healthy urban environment, the prerequisite for which is the preservation of natural structures and functions in cities. Cities should aim for closed water cycles (e.g. use of rainwater), a high degree of waste recovery and reuse, energy generation from renewable sources, and a high proportion of green areas in the city structure (e.g. green roofs) (Hammer et al., 2011). As the literature review showed, spatial planning, with identified land use trends, is an important but underutilised instrument for climate protection and climate change adaptation. Insufficient consideration is given to planning for climate change which makes it possible to combat the effects and causes of urban heat islands.

5. Conclusion

Implementing the principle of polyfunctional development of individual areas is crucial to urban spatial management. The spatial economy and the diversity of functions introduced are important to counteract the negative processes that exacerbate climate change and the resulting consequences. The design of a city's spatial structure should be seen from the perspective of the entire city and its functional areas, rather than individual neighbourhoods. The research results indicate a failure to recognise the relationship between spatial planning and climate change, climate change adaptation, or climate policy more broadly.

Ecosystem services, understood as a set of direct and indirect benefits related to the functioning of ecosystems for society and the economy, are not highlighted in the spatial policies of the studied cities. It is characteristic that the number of areas providing them is limited, and their potential is weakened by limiting biodiversity. Yet, it is spatial planning that can significantly determine cities' climate policies. There is a need to monitor and forecast land-use changes, for which research has shown that planners can use Markov chains. This action increases the chances of effectively implementing specific climate change adaptation measures through land-use planning.

Stimulating urban metabolism through a high-quality natural environment and applying nature-based solutions to urban development is key to sustaining effective urban organisation and structure (Lucertini & Musco, 2020). Furthermore, it contributes to the acquisition and stimulation of urban resilience, i.e. the capacity of the urban system (social, economic, infrastructural) to maintain or rapidly return to desired functions in the face of disruption and to adapt to change and rapidly transform the system to new conditions that constrain current or future adaptive capacity (Meerow et al., 2016). Building ecosystem viability is important for maintaining the capacity to regenerate and provide particular services (ecosystem services) and the potential of nature and its resources to mitigate climate risks (water management, space management).

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Appendix

Table Temporal change and percentage of land cover classes in Brno, Kosice, Lodz, Miskolc for the study period in km²

Brno						
	2006		**2012**		**2018**	
Land cover	Area [km2]	Area [%]	Area [km2]	Area [%]	Area [km2]	Area [%]
green spaces	144.70	62.86	143.20	62.21	140.65	61.10
infrastructure	13.7	5.95	14.09	6.12	15.58	6.77
industry and services	27.63	12.00	28.72	12.48	29.10	12.64
residential areas	44.17	19.19	44.19	19.20	44.87	19.49
Total	230.21	100	230.21	100	230.21	100.00
Kosice						
	2006		**2012**		**2018**	
Land cover	Area [km2]	Area [%]	Area [km2]	Area [%]	Area [km2]	Area [%]
green spaces	185.43	76.06	184.00	75.48	182.56	74.89
infrastructure	12.29	5.04	12.32	5.05	12.33	5.06
industry and services	25.15	10.31	26.00	10.67	26.19	10.74
residential areas	20.92	8.58	21.46	8.80	22.71	9.32
Total	243.79	100	243.79	100.00	243.79	100.00
Lodz						
	2006		**2012**		**2018**	
Land cover	Area [km2]	Area [%]	Area [km2]	Area [%]	Area [km2]	Area [%]
green spaces	169.13	57.69	166.42	56.77	159.91	54.55
infrastructure	19.16	6.54	19.76	6.74	21.09	7.19
industry and services	37.50	12.79	38.11	13.00	40.14	13.69
residential areas	67.36	22.98	68.86	23.49	72.01	24.57
Total	293.15	100.00	293.15	100.00	293.15	100.00
Miskolc						
	2006		**2012**		**2018**	
Land cover	Area [km2]	Area [%]	Area [km2]	Area [%]	Area [km2]	Area [%]
green spaces	190.59	80.57	187.67	79.34	186.39	78.80
infrastructure	8.70	3.68	8.55	3.61	8.83	3.73
industry and services	14.20	6.00	15.17	6.41	15.91	6.73