MONITORING LAND-USE DYNAMICS IN ROMANIA'S MAJOR METROPOLITAN AREAS

MONITORIZACIÓN DE LAS DINÁMICAS DE USO DEL SUELO EN LAS PRINCIPALES ÁREAS METROPOLITANAS DE RUMANÍA

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Abstract

The study examines land use and land cover changes (LUCC) in Romania's seven largest metropolitan areas from 2000 to 2018, concentrating on trends and their driving forces at the national level. The multitemporal analysis was conducted utilising GIS tools to track changes in urban, agricultural, and natural land categories. To increase accuracy, high-resolution satellite imagery and reclassification methods were also used, providing more reliable results. The detected results were linked to demographic data to highlight the dynamics of population pressure, economic growth, and infrastructure development. By identifying the common causes of land-use changes, the main trends were presented, along with local territorial and socioeconomic specificities. The results reflect the challenges the country is facing due to increasing suburbanisation and land-use fragmentation and illustrate the need for context-specific urban planning methods.

Keywords

Romania; land-use dynamics; metropolitan areas; urban sprawl; territorial planning

Resumen

El estudio examina los cambios de usos del suelo en las siete áreas metropolitanas más importantes de Rumanía entre los años 2000 y 2018. Se han analizado las tendencias y sus respectivos determinantes a nivel nacional. Para el análisis multitemporal se emplearon herramientas SIG que permitieron rastrear los cambios en las categorías de uso del suelo artificial, agrícola y natural. A fin de aumentar

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la precisión, también se usaron imágenes de satélite de alta resolución y métodos de reclasificación que proporcionaron resultados más fiables. Se vincularon los resultados detectados con datos demográficos con el fin de evidenciar las dinámicas de presión poblacional, crecimiento económico y desarrollo de infraestructura. Al identificar las causas comunes de los cambios en el uso del suelo, se presentaron, por un lado, las principales tendencias generales y, por otro lado, las particularidades territoriales y socioeconómicas locales. Los resultados reflejan las dificultades a las que se enfrenta el país a raíz del aumento de la suburbanización y la fragmentación del uso del suelo e ilustran la necesidad de aplicar métodos de planificación urbana adaptados a cada contexto.

Palabras clave

Rumanía; dinámicas de uso del suelo; áreas metropolitanas; expansión urbana; ordenación territorial

1. INTRODUCTION

Urbanisation is one of the main drivers of LUCC dynamics, reshaping the landscape and affecting ecosystems (Nuissl and Siedentop, 2021; Izakovičová et al., 2017; Abdo and Prakash, 2020; Alberti, 2005; Brunori et al., 2017). During the post-socialist era, urban growth has been particularly rapid in Romania (Sandu and Groza, 2017; Mihai et al., 2015), especially in metropolitan areas (MAs), inducing considerable LUCC (Grigorescu et al., 2012). Such shifts are to be expected when changing environment emerges from socioeconomic development, policy reforms and EU membership.

This study concentrates on the seven major metropolitan areas (MMAs) of Romania: Bucharest, Cluj-Napoca, Constanța, Brașov, Craiova, Iași, and Timișoara. These MMAs are economic hubs, focal points for urbanisation, and essential areas in the analysis of LUCC. Knowledge regarding patterns and drivers of LUCC in these regions is indispensable for effective territorial planning and ensuring sustainable development.

The establishment of MAs was regulated by Law No. 351/2001 on the National Spatial Development Plan. This law, updated in 2011, allowed the formation of MAs for the capital and first-tier municipalities, with the aim of strengthening the complementarity of the territorial development process. The legal framework aims to provide better coordination in regional development while responding to the emerging pressures of urbanisation. However, the implementation of these areas revealed complex challenges in urban and regional planning that remain underexplored.

The general hypothesis of this study is that, despite all the significant differences between MMAs, there are general mechanisms influencing LUCC. If validated, this hypothesis may lead to better territorial planning and metropolitan space management. Uncovering common LUCC processes amongst MMAs can aid in the development of better planning approaches. These measures, adjusted to the individual settings of each MMA, should help to achieve balanced and sustainable urban growth on a national scale. Our main contribution lies in simultaneously analysing seven MMAs, offering key insights into Romania's urban transformation. Specifically, our research addresses the need for a comprehensive understanding of metropolitan transformations by: (1) Identifying shared LUCC mechanisms across different geographical and socioeconomic contexts; (2) Highlighting the unique spatial dynamics of each MMA; (3) Providing insights that can inform more targeted territorial planning approaches.

The article is structured as follows. The first section will focus on the literature review, while also highlighting the research gap we aim to contribute to. Next, the data sources, methodological framework and GIS techniques used to analyse LUCC are described in depth. The results section highlights agricultural change and urbanisation as the main drivers of LUCC, and the discussion interprets these results in light of territorial cohesion and environmental issues. The study's wider ramifications and its contribution to understanding LUCC dynamics in MAs are addressed in the paper's conclusion.

1.1. LITERATURE REVIEW

In Central and Eastern (CEE) European countries, the transition from a centrally planned urban system to one shaped by market economy resulted in numerous LUCC, as priorities shifted from an industrial and residential focus to more unpredictable variables such as market demands, land prices and privatisation, to name just a few (Stanilov, 2007). Indeed, as these market-driven shifts progressed, the consequences for LULC became more complicated. The introduction of private ownership led to an increase in speculative development, which frequently prioritises short-term economic interests above sustainable practices, leading to urban sprawl and environmental deterioration (Feranec et al., 2017; Pichler-Milanović et al., 2007).

Therefore, in this context of post-socialist urban transformation, understanding and measuring these changes is essential. LUCC research uses remote sensing and GIS tools to measure and evaluate changes over time (Cheruto et al., 2016; Roy & Roy, 2010). The changes are triggered by a variety of socioeconomic activities and natural events, such as population growth, climate change, or terrain (Cheruto et al., 2016; Roy & Roy, 2010). LUCC has a profound influence on ecosystems, affecting nutrient cycles, hydrology, species diversity and facilitating the spread of invasive species and diseases (Jarnagin et al., 2004). Consistent LUCC mapping is vital for natural resource management and future change projections (Cheruto et al., 2016; Roy & Roy, 2010).

These transitions are common in all CEE states as a result of the shared post-socialist urban dynamics, but their magnitude and geographical patterns vary considerably among regions and countries (Sandu, 2023; Schmidt et al., 2015). MAs are the locations where such changes are most evident (Nuissl and Siedentop, 2021). These areas frequently bear the brunt of rapid urban developments, which makes them require well-targeted policy measures to successfully manage the problems and opportunities brought by urbanisation (Coudroy De Lille, 2008).

Indeed, the complex LULC changes have been documented in the literature. Sýkora and Bouzarovski (2012) highlighted that these transformations were multi-layered processes involving not only the morphological and functional dimensions but also the institutional and socio-economic ones, and unfolded at different speeds and scales. Often, these processes manifested as similar patterns of commercial suburbanisation followed by residential sprawl, accompanied by a proliferation of brownfields and a notable scarcity of green urban areas amidst intense urban sprawl (Sandu, 2023; Cudny & Kunc, 2022; Schmidt et al., 2015; Stanilov, 2007). Additionally, these spatial transformations were further shaped by the restitution of land to its previous owners, which led to increased land fragmentation and also increased abandonment of agricultural land (Bański & Kamińska, 2022; Turnock, 1996). However, as Hirt (2013) highlights, the specific spatial and socio-economic transformations varied across the regions due to differences not only in the pre-socialist urban morphologies, but also in institutional capacities and privatisation strategies. While Poland, Czechia, Bulgaria, and Hungary have received a lot of scholarly attention (Stanilov, 2007; Hirt, 2007; Kok & Kovács, 1999; Sýkora, 1999), Romania's specific trajectories remain comparatively understudied. Most of the studies have focused on major cities, with particular attention being given to Bucharest, but comparative analyses of metropolitan areas remain scarce (Cocheci and Petrișor, 2023a). This research gap is particularly important given Romania's specific transition processes, with urban sprawl that has accelerated following EU accession, resulting in unique temporalities in its LULC changes (Petrișor & Petrișor, 2018) that warrant more analysis within the broader CEE context. Therefore, this study addresses this limitation by adopting a comprehensive approach that goes beyond individual city analyses. By examining seven major MAs simultaneously, while also considering the interplay of socioeconomic and demographic factors, we aim to uncover both the common mechanisms and local variations that characterise land-use changes in post-socialist urban contexts.

In Romania, the framework for metropolitan and regional development was established in accordance with European policies supporting polycentric urbanisation (Brad, 2021; Mitrică et al., 2014; Vele et al., 2016; Benedek, 2006). A turning point took place in 1997, when the European Commission's Habitat Directive underlined the need of balanced urban systems by recognising cities as regional capitals, supporting diverse economies and implementing contemporary urban management approaches. In response, Romania adopted these ideas into its territorial policies, establishing development regions in 1997, MAs in 2011, and, subsequently, growth poles, all of which are incorporated into the National Spatial Development Plan (PATN) and National Development Strategy.

Accession to the EU in 2007 marked one of the most important turning points in the urban development of Romania. Its alignment with EU policy highlighted the need to develop urban planning frameworks that could balance economic growth and environmental concerns. The Romanian Urban Policy was developed to foster sustainable, inclusive and resilient urban development in conformity with the EU's Urban Agenda (World Bank, 2021). Indeed, Romanian MAs present a distinct case of urban transformation. Unlike more extensively studied regions, these areas reflect a complex interplay of historical legacies, rapid economic restructuring, and emerging urban planning frameworks. The period following EU accession in 2007 marked a turning point, accelerating urban sprawl and land-use changes in ways that require nuanced, context-specific investigation.

Since the post-socialist transition, land has been affected by constant transformations in Romania. Deforestation and urbanisation have emerged as primary drivers, accounting for approximately 75% of all changes (Petrisor & Petrişor, 2017, 2018, 2021). Changes in land cover due to urbanisation have been noticed within MAs, with effects on ecological systems, landscape fragmentation, and degradation of natural landscapes (Cocheci and Petrișor, 2023b). Agricultural land has decreased, especially near urban areas, as built-up areas expand (Grigorescu et al., 2019). Property restitution after the 1989 revolution led to the fragmentation of agricultural plots, as well as instability within the agro-systems (Ursu et al., 2007). Recent research has shown ongoing deforestation and agricultural abandonment connected to post-socialist property restitution (Petrisor & Petrişor, 2021). Human activity, such as urbanisation, agricultural growth and deforestation, puts strain on natural protected areas. These changes in land use are the result of socioeconomic transitions on land use patterns, with regional differences seen throughout Romania's development areas (Grigorescu et al., 2019; Petrisor and Petrişor, 2017). Understanding these interactions is critical for sustainable land management and environmental preservation.

In terms of future land use changes, Grigorescu et al. (2019) examined urban sprawl in Romania based on expected LUCC between 2007 and 2050, and projected a rise in built-up area mainly as a result of a decrease in crops, both within and outside the city borders. If the projections are correct, the continuation of these trends may jeopardise the sustainability of urban development, underscoring the need to implement strategies that mitigate the adverse effects of urban sprawl and preserve vital agricultural land.

2. MATERIALS AND METHODS

2.1. STUDY AREAS

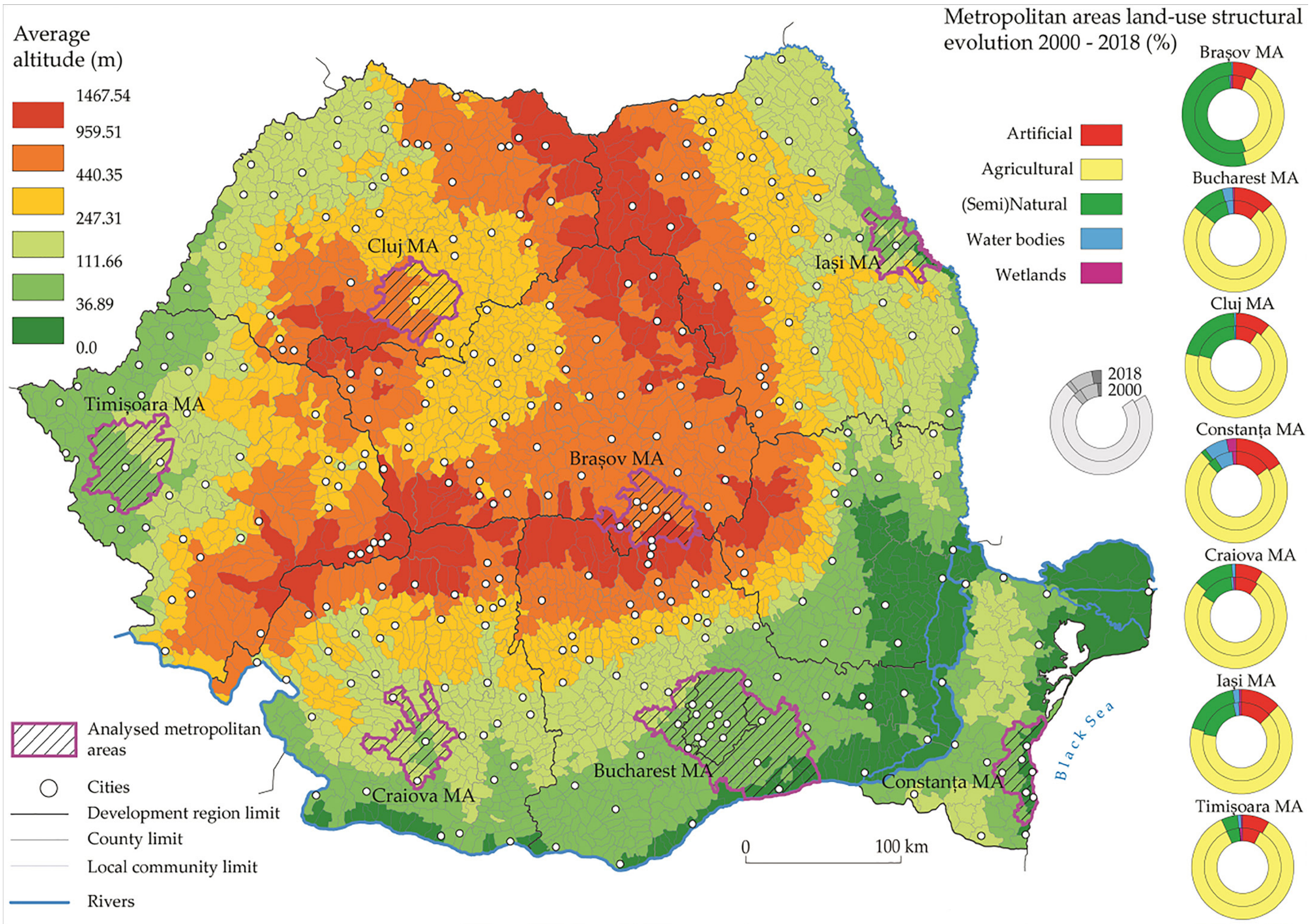

FIGURE 1. LOCALISATION OF THE 7 ANALYSED MMAS

The study areas were selected following a prioritisation process of the most important MAs in Romania, in 2019[4]. The analysed MMAs were selected in order to offer representation of each development region while also including a diverse range of natural habitats. This method attempts to capture the many geographic, socioeconomic, and ecological particularities found in Romania, allowing for a full assessment of LUCC between 2000 and 2018. By considering MMAs in a variety of natural environments, from mountainous terrains to plains and coastal zones, the study offers insights on how regional and local variables influence urbanisation dynamics and environmental shifts. This methodological choice boosts the findings' relevance and application for different contexts all throughout the country.

2.2. SOURCES AND METHODOLOGY

The initial data was processed by a systematic reduction of the 44 classes from the CORINE Land Cover (CLC) inventory to 5 major classes. This methodological choice aimed to mitigate the number of potential inaccuracies caused by the diversity of methods implemented in the CLC program with the evolution of satellite databases. The simplification process adhered to the, CLC nomenclature main classification scheme : 1. Artificial Area; 2. Agricultural Area; 3. Natural/Semi-natural Area; 4. Wetlands; 5. Water Bodies; According to this classification scheme, land use classes are defined by textures, patterns and densities of elements, like artificial structures, crops, trees, water courses, and similar categories. Such data (CLC) are often used in analyses at European or national level, or regionally with relatively reliable results (Diaz-Pacheco and Gutiérrez, 2014; Guérois, 2003).

To capture the dynamics of land use, the data used to establish changes at the territorial level included LULC images for the year 2000 and were compared with the data obtained from LULC images for the year 2018. The cartographic representations obtained by processing the data of the CLC monitoring service were verified by superimposing them on high-resolution satellite imagery, in order to visually inspect the quality of the data set after the simplification process. The images used to validate spatial accuracy were obtained from the United States Geological Survey website using the EarthExplorer function. This validation process ensured the accuracy and reliability of the simplified dataset.

As the selected software does not include a built-in tool for land use change detection, a simplified custom method was developed to address this limitation. A series of GIS techniques were implemented to analyse the changes that occurred at the metropolitan level. Among these is "pixel-over-pixel comparison" through which the changes at the pixel level were analysed following the simplification process. Beyond the simplification, the data also went through a provisional reclassification

4. The study was conducted in 2019 and utilises data available at that moment, includig MA's configurations that predate the creation of a specific law for MAs, namely Law no. 246/2022. The structures as presented are relevant for understanding the exact conditions that led to significant shifts in land use and the period of most substantial urban expansion after the fall of the communist regime.

process. Thus, in order to highlight a certain type of change at the spatial level, the data were gradually reclassified, being brought to the initial form for subsequent processes. For example, to highlight the transformations that occurred at the level of artificial areas in a certain MA, these were marked with the number 1, and the rest of the areas were marked with the number 11 to highlight the transitions from artificial to other major types of land use. Thus, the database includes separate entries for each type of transformation in the 7 MAs. This method has proven to be both effective and reliable. It detects 100% of altered pixels without error and is supported by a tool designed to process two raster images and identify all pixel-level differences, as well as the nature of those changes. While the raw output requires user interpretation, the reclassification step enhances the clarity and accuracy of results, helping to compensate for known classification errors within the CLC dataset, particularly in subcategories of major land uses. In order to decipher the results, the following calculation formula was implemented for all land cover typologies in each area:

LULC change for X land use category = LULC image of 2000 (simplified and reclassified) x 2 + LULC image of 2018 (simplified and reclassified)

The formula was applied after each reclassification process, for each LULC category and repeated in all MAs. The results included, in addition to the areas affected by the changes, the unchanged areas within each use category. The "Unspecified" category remained because all processes for detecting transformations were carried out individually and then combined. For example, when determining which parcels of land transitioned from one major category to another, the remaining territory was marked as "Unspecified" or "Unchanged." This designation indicates that the land either did not change from the specific category being analysed to another or reflects changes originating from a different category not currently under analysis.

The study acknowledges several key limitations in land-use change detection. Potential sources of uncertainty include variations in satellite image quality (such as seasonal differences in land cover appearance) and the complexity of interpreting urban–rural landscape transitions (García-Álvarez et al., 2022). The reclassification represents a deliberate methodological trade-off between the level of detail and practical interpretability, aiming to maintain classification accuracy in line with accepted guidelines.

Furthermore, a series of statistical data provided by The National Institute of Statistics in Romania (NIS) through the TEMPO database was used to supplement the information on the seven MAs, but also to examine how they are positioned on the national level. Data acquistion involved extracting key variables such as population, total area, building permits, total square meters authorised, dwellings built for each MAs for the period between 2002 – 2018, due to data availability. One exception was the demographic data for which we calculated the growth rate starting from 2000, as data was available. Attention was given to removing potential outliers and addresing any inconsistencies in reporting across different MAs. These demographic and socioeconomic indicators will complement the spatial data by offering additional insights on how demographic pressure and socio-economic transformations intersect with LUCC in Romania.

3. RESULTS

The study identifies a number of general and local factors impacting LUCC in the MMAs. These dynamics reflect both broad trends and unique geographical factors that influence the spatial development of these regions.

Table 1 depicts the geographical distribution of population and land use throughout Romanian MAs, revealing major geographic patterns that highlight the link between major urban cores and surrounding territorial administrative units (TAUs). Central cities, like Bucharest and Cluj-Napoca, serve as dominant nodes, concentrating a large proportion of the population and economic activity in fairly small territories. For instance, Bucharest represents just 4.52% of its MA's surface but concentrates over 75% of the total population. Such extreme concentration puts intense urban pressure on the core while leaving the surrounding TAUs to absorb impacts brought about by suburbanisation and urban sprawl.

Peripheral TAUs, which account for the majority of the land area in most MAs, have a peculiar dynamic. These regions serve as expansion zones, absorbing a substantial amount of residential and commercial development. The large number of construction licenses and residences built in these TAUs, particularly in Timișoara and Iaşi, illustrates an exurbanisation trend driven by land availability and cheaper development costs. This geographic mismatch highlights the necessity of integrated territorial planning in managing the transition from congested urban cores to more scattered suburban and peri-urban landscapes, assuring long-term growth while safeguarding natural and agricultural areas.

TABLE 1. THE RELATIONSHIPS BETWEEN THE AREAS AND POPULATIONS OF URBAN CORES AND THE REMAINING TAUS WITHIN EACH ANALYSED MA

		Population** (number)	Area (Sq.Km)	Building permits delivered between 2002 and 2018***	Total sq. meters authorised between 2002 and 2018	Dwellings built between 2000 and 2018
BRAŞOV MA	**Total Metropolitan Area**	**478.300**	**1.693,18**	**14.658**	**7.673.935**	**22.773**
	Central city (Brașov)	289.360	186,94	4.167	4.886.717	13.958
	Other TAUs* of the MA	188.940	1.506,24	10.491	2.787.218	8.815
	Other TAUs of the MA (%)*	*39,50*	*88,96*	*71,57*	*36,32*	*38,71*
BUCHAREST MA	**Total Metropolitan Area**	**2.841.831**	**5.313,00**	**109.931**	**43.567.397**	**138.834**
	Central city (Bucharest)	2.131.034	240,35	20.231	22.650.240	49.878
	Other TAUs* of the MA	710.797	5.072,66	89.700	20.917.157	88.956
	Other TAUs of the MA (%)*	*25,01*	*95,48*	*81,60*	*48,01*	*64,07*

CLUJ MA	**Total Metropolitan Area**	**438.748**	**1.740,56**	**24.314**	**11.563.199**	**54.873**
	Central city (Cluj-Napoca)	324.960	179,23	10.422	6.717.875	24.492
	Other TAUs* of the MA	113.788	1.561,33	13.892	4.845.324	30.381
	Other TAUs of the MA (%)*	*25,93*	*89,70*	*57,14*	*41,90*	*55,37*
CONSTANŢA MA	**Total Metropolitan Area**	**491.108**	**1.110,28**	**27.040**	**7.905.077**	**42.712**
	Central city (Constanța)	313.021	124,77	5.871	3.645.686	19.513
	Other TAUs* of the MA	178.087	985,52	21.169	4.259.391	23.199
	Other TAUs of the MA (%)*	*36,26*	*88,76*	*78,29*	*53,88*	*54,31*
CRAIOVA MA	**Total Metropolitan Area**	**398.154**	**1.579,29**	**16.206**	**4.049.443**	**13.615**
	Central city (Craiova)	301.269	81,97	7.768	2.612.026	7.741
	Other TAUs* of the MA	96.885	1.497,32	8.438	1.437.417	5.874
	Other TAUs of the MA (%)*	*24,33*	*94,81*	*52,07*	*35,50*	*43,14*
IAŞI MA	**Total Metropolitan Area**	**521.369**	**1.092,08**	**24.915**	**5.259.766**	**27.359**
	Central city (Iași)	378.954	91,51	6.113	1.994.223	11.423
	Other TAUs* of the MA	142.415	1.000,56	18.802	3.265.543	15.936
	Other TAUs of the MA (%)*	*27,32*	*91,62*	*75,46*	*62,09*	*58,25*
TIMIŞOARA MA	**Total Metropolitan Area**	**476.293**	**2.294,94**	**29.159**	**9.120.794**	**32.235**
	Central city (Timișoara)	328.186	129,33	5.677	3.576.421	9.283
	Other TAUs* of the MA	148.107	2.165,62	23.482	5.544.373	22.952
	Other TAUs of the MA (%)*	*31,10*	*94,36*	*80,53*	*60,79*	*71,20*
NATIONAL	**Total ROMANIA**	**22.170.586**	**238.396,52**	**860.658**	**205.535.335**	**829.089**
	Total all 7 Metropolitan Areas	5.645.803	14.823,33	246.223	89.139.611	332.401
	Total all 7 Metropolitan Areas (%)	*25,47*	*6,22*	*28,61*	*43,37*	*40,09*

*TAU = Territorial Administrative Unit; **1st January 2019; ***Data available since 2002.
Data source: INSSE - TEMPO, 2019

A dominant factor is exurbanisation— resulting from the migration from urban centres to outlying TAUs. This practice causes the expansion of residential areas and the loss of agricultural land. At the same time, agricultural modernisation, including the construction of farms, greenhouses, or storage facilities, has a double impact: it increases land-use pressure in high-density rural areas (such as Iași and Craiova) while adjusting to changing economic needs. This conflict is most noticeable in areas where rural residents exert significant pressure on limited land resources.

Local particularities also play an important role: natural factors such as geomorphological and hydrographic conditions intersect with anthropogenic influences such as economic dynamics and transport networks to create unique LUCC patterns. Thus, MAs with robust economic activity and well-developed transport corridors (e.g., Cluj-Napoca and Timişoara) show a more balanced interplay between urban and rural development, while other regions, such as Bucharest and Braşov, are experiencing slower growth in the centre and increasing pressure on the peripheral TAUs.

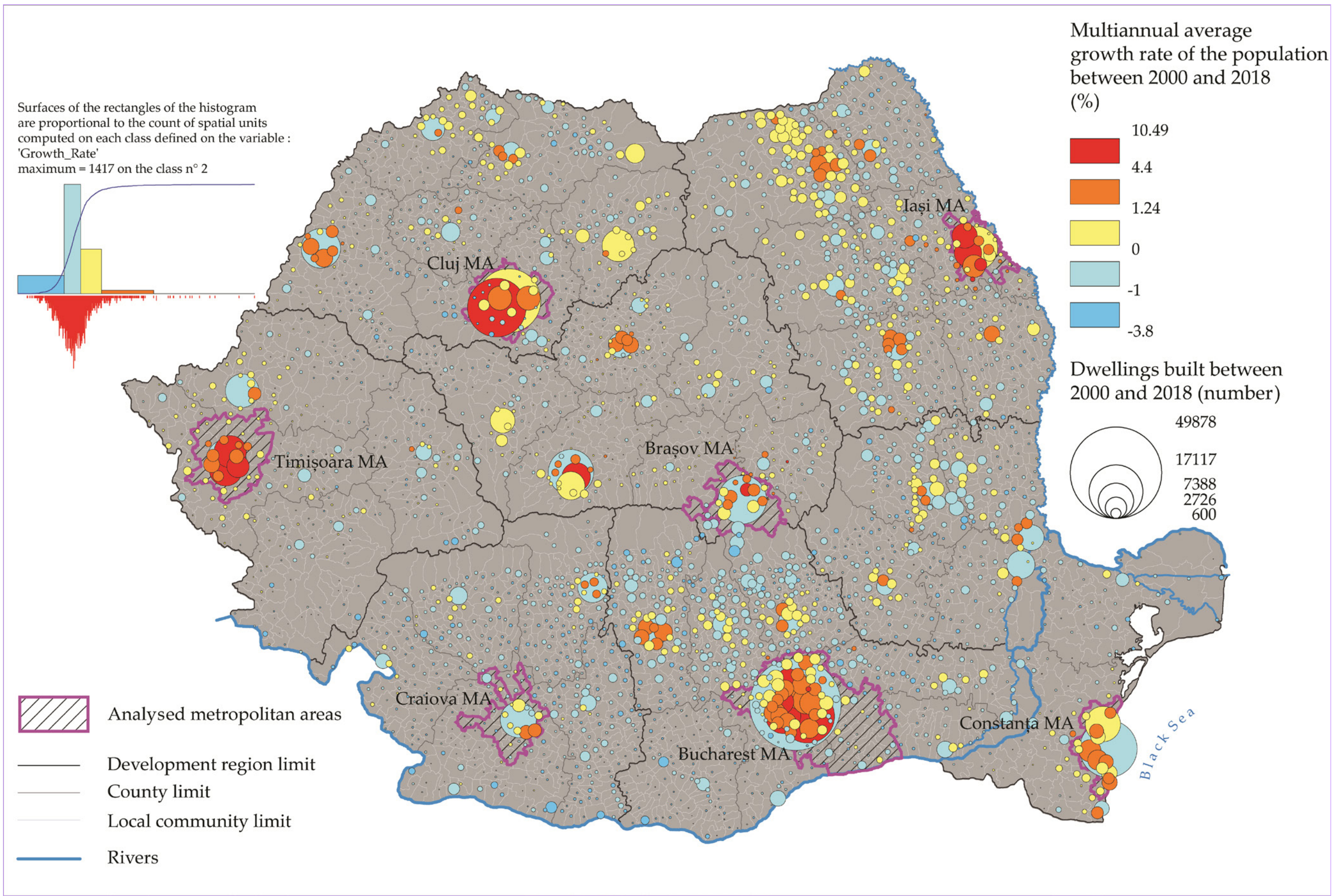

FIGURE 2. URBAN GROWTH TRENDS IN THE ANALYSED MMAS

The trends shown in Figure 2 further illustrate this dynamic: while Timişoara is experiencing growth in its urban centre, other cities (e.g., Bucharest, Braşov and Constanța) have stagnant or negative growth rates. This stagnation leads to increasing pressure on the surrounding TAUs, intensifying suburbanisation and land use fragmentation. The resulting patterns highlight the need for a comprehensive national strategy that takes into account the local geographical characteristics to effectively address the diverse challenges of spatial management in these MAs.

The examination of LULC dynamics across Romanian MAs provides valuable insights into the forces shaping spatial transformations (tables 2 and 3). The data reveals common trends, such as suburbanisation and agricultural modernisation, but also emphasises the importance of local context—geography and socioeconomic factors all play a role. This supports the article's argument that, despite the diversity of MAs, underlying factors shape their growth paths.

The analysis makes a substantial contribution by identifying artificial surfaces (ART) as one of the dominant receptor categories across all study areas. This demonstrates the ubiquitous effect of urbanisation, which promotes the conversion of agricultural land and natural surfaces into built environments. The trends depicted in the tables show empirical evidence of urban sprawl and demonstrate the importance of integrated planning in managing the fast growth of metropolitan peripheries. This approach is consistent with the article's overall goal of clarifying how urbanisation pressure affects land-use patterns.

Another important finding is the double role of agricultural land (AGR) as both a major emitter and, in certain cases, a major receptor of land-use change. In peri-urban and surrounding rural areas near cities like Iași and Craiova, farmland is still under massive pressure from local populations, which in some cases leads to its expansion. These dynamics highlight the complicated relationship between the rural population and land-use patterns in MMAs, pointing to the need for policies that account for urban growth and agricultural practices.

The analysis also points to the environmental implications of these land-use shifts. The sharp decrease of wetlands and natural surfaces across multiple MAs reflects larger patterns of ecological degradation, frequently intensified by urban growth and agricultural intensification (Ursu et al., 2020). However, small anomalies, such as wetland area increases in Constanța, highlight the possibility for targeted conservation initiatives. These findings show the importance of conservation efforts in metropolitan planning endeavours.

Overall, the data presented in the tables add to the study by offering a more nuanced picture of the spatial and temporal dynamics of LULC in Romanian urban and periurban regions. They validate the hypothesis that shared mechanisms influence these transformations while also accounting for local specificities. These findings are crucial for informing sustainable development policies that address the diverse challenges faced by metropolitan regions.

TABLE 2. GENERAL AND STRUCTURAL LUCC DYNAMICS OF THE 7 ANALYSED MMAS (2000 - 2018)

		ART	AGR	NAT	WAT	WET	*Total gain (ha)*	*% of total MA*
Brașov MA	to ART	...	3.777,2	485,4	129,7	189,2	*4.581,4*	*2,71*
	to AGR	740,6	...	2.068,0	147,5	1.655,5	*4.611,5*	*2,72*
	to NAT	84,4	2.362,1	...	113,4	9,8	*2.569,7*	*1,52*
	to WAT	0,3	153,5	5,9	...	33,4	*193,1*	*0,11*
	to WET	0,0	0,0	0,0	0,0	...	*0,0*	*0,00*
	Total loss (Ha)	*825,2*	*6.292,7*	*2.559,2*	*390,6*	*1.888,0*	***11.955,7***	***7,06***
	% of total MA	*0,49*	*3,72*	*1,51*	*0,23*	*1,12*	***7,06***	
Bucharest MA	to ART	...	17.317,4	582,6	370,1	111,3	*18.381,3*	*3,46*
	to AGR	6.607,2	...	1.811,3	378,8	463,4	*9.260,8*	*1,74*
	to NAT	103,1	2.177,6	...	133,6	215,1	*2.629,5*	*0,49*
	to WAT	123,8	1.110,6	810,8	...	1.006,0	*3.051,2*	*0,57*
	to WET	48,9	796,9	646,8	329,7	...	*1.822,4*	*0,34*
	Total loss (Ha)	*6.883,1*	*21.402,6*	*3.851,5*	*1.212,2*	*1.795,8*	***35.145,1***	***6,62***
	% of total MA	*1,30*	*4,03*	*0,73*	*0,23*	*0,34*	***6,62***	

Cluj MA	**to ART**	...	3.664,4	151,3	149,5	0,4	*3.965,6*	*2,28*
	to AGR	781,5	...	1.573,1	233,3	97,8	*2.685,6*	*1,54*
	to NAT	31,3	3.130,3	...	12,0	0,0	*3.142,3*	*1,81*
	to WAT	1,6	34,6	0,3	...	54,7	*91,3*	*0,05*
	to WET	0,0	28,8	0,0	0,0	...	*28,8*	*0,02*
	Total loss (Ha)	*814,4*	*6.858,1*	*1.724,7*	*394,8*	*152,8*	***9.944,8***	***5,71***
	% of total MA	*0,47*	*3,94*	*0,99*	*0,23*	*0,09*	***5,71***	
Constanța MA	**to ART**	...	2.205,3	211,1	217,1	120,5	*2.753,9*	*2,48*
	to AGR	1.224,0	...	606,8	36,3	134,3	*2.001,3*	*1,81*
	to NAT	17,1	43,4	...	28,1	60,6	*149,3*	*0,13*
	to WAT	65,0	31,6	3,0	...	17,1	*116,7*	*0,11*
	to WET	97,6	26,3	1.640,3	155,8	...	*1.919,9*	*1,73*
	Total loss (Ha)	*1.403,7*	*2.306,5*	*2.461,1*	*437,3*	*332,5*	***6.941,1***	***6,26***
	% of total MA	*1,27*	*2,08*	*2,22*	*0,39*	*0,30*	***6,26***	
Craiova MA	**to ART**	...	2.165,3	108,5	4,1	250,4	*2.528,3*	*1,60*
	to AGR	3.621,5	...	3.330,7	35,6	1.068,5	*8.056,3*	*5,10*
	to NAT	157,5	851,9	...	36,0	44,5	*1.089,9*	*0,69*
	to WAT	16,8	204,6	83,8	...	187,3	*492,5*	*0,31*
	to WET	0,0	35,0	5,4	0,0	...	*40,4*	*0,03*
	Total loss (Ha)	*3.795,8*	*3.256,8*	*3.528,4*	*75,6*	*1.550,7*	***12.207,4***	***7,73***
	% of total MA	*2,40*	*2,06*	*2,23*	*0,05*	*0,98*	***7,73***	
Iași MA	**to ART**	...	2.178,9	73,3	40,5	103,7	*2.396,4*	*2,19*
	to AGR	2.356,4	...	1.636,9	574,7	725,6	*5.293,5*	*4,85*
	to NAT	271,3	1.026,1	...	10,2	16,1	*1.323,7*	*1,21*
	to WAT	22,7	300,0	74,7	...	62,8	*460,2*	*0,42*
	to WET	65,4	323,5	10,7	104,5	...	*504,1*	*0,46*
	Total loss (Ha)	*2.715,8*	*3.828,6*	*1.795,6*	*729,8*	*908,2*	***9.978,1***	***9,14***
	% of total MA	*2,49*	*3,51*	*1,64*	*0,67*	*0,83*	***9,14***	
Timișoara MA	**to ART**	...	4.205,0	113,9	0,3	41,5	*4.360,8*	*1,90*
	to AGR	1.586,6	...	1.804,1	22,4	1.657,2	*5.070,3*	*2,21*
	to NAT	41,6	1.311,7	...	0,1	0,4	*1.353,8*	*0,59*
	to WAT	102,1	1.682,6	1,4	...	332,6	*2.118,6*	*0,92*
	to WET	63,6	278,6	0	71,8	...	*414,0*	*0,18*
	Total loss (Ha)	*1.793,8*	*7.477,9*	*1.919,5*	*94,6*	*2.031,6*	***13.317,5***	***5,80***
	% of total MA	*0,78*	*3,26*	*0,84*	*0,04*	*0,89*	***5,80***	

TABLE 3. LUCC DYNAMICS IN THE ANALYSED MMAS (2000 - 2018)

		Area_2000 (ha)	Area_2018 (ha)	Unchanged 2000-2018	Gain 2000_2018	Loss 2000-2018	Difference gain-loss 2000-2018	Multiannual average growth rate
Brașov MA	ART	9.455,1	13.211,3	8.629,9	4.581,4	825,2	3.756,2	1,88
	AGR	66.127,9	64.446,7	59.835,1	4.611,5	6.292,7	-1.681,2	-0,14
	NAT	90.773,1	90.783,6	88.213,9	2.569,7	2.559,2	10,5	0,00
	WAT	1.073,6	876,0	682,9	193,1	390,6	-197,6	-1,12
	WET	1.888,0	0,0	0,0	0,0	1.888,0	-1.888,0	-100,00
București MA	ART	57.347,3	68.845,5	50.464,2	18.381,3	6.883,1	11.498,2	1,02
	AGR	398.876,3	386.734,5	377.473,7	9.260,8	21.402,6	-12.141,8	-0,17
	NAT	55.547,7	54.325,8	51.696,2	2.629,5	3.851,5	-1.221,9	-0,12
	WAT	16.299,0	18.138,0	15.086,8	3.051,2	1.212,2	1.839,0	0,60
	WET	3.149,3	3.175,9	1.353,5	1.822,4	1.795,8	26,6	0,05
Cluj MA	ART	16.165,6	19.316,8	15.351,2	3.965,6	814,4	3.151,2	0,99
	AGR	121.703,2	117.530,7	114.845,1	2.685,6	6.858,1	-4.172,5	-0,19
	NAT	34.653,1	36.070,7	32.928,4	3.142,3	1.724,7	1.417,6	0,22
	WAT	1.367,2	1.063,7	972,4	91,3	394,8	-303,5	-1,38
	WET	167,6	43,5	14,8	28,8	152,8	-124,1	-7,22
Constanța MA	ART	16.729,4	18.079,6	15.325,7	2.753,9	1.403,7	1.350,2	0,43
	AGR	79.827,1	79.522,0	77.520,7	2.001,3	2.306,5	-305,1	-0,02
	NAT	4.003,7	1.691,9	1.542,6	149,3	2.461,1	-2.311,8	-4,67
	WAT	8.375,8	8.055,2	7.938,5	116,7	437,3	-320,6	-0,22
	WET	1.906,1	3.493,5	1.573,6	1.919,9	332,5	1.587,4	3,42
Craiova MA	ART	14.996,9	13.729,4	11.201,2	2.528,3	3.795,8	-1.267,5	-0,49
	AGR	117.450,5	122.249,9	114.193,7	8.056,3	3.256,8	4.799,4	0,22
	NAT	22.432,0	19.993,5	18.903,6	1.089,9	3.528,4	-2.438,5	-0,64
	WAT	1.498,8	1.915,7	1.423,2	492,5	75,6	416,9	1,37
	WET	1.550,7	40,4	0,0	40,4	1.550,7	-1.510,3	-18,35
Iași MA	ART	14.301,5	13.982,1	11.585,7	2.396,4	2.715,8	-319,4	-0,13
	AGR	71.085,7	72.550,6	67.257,1	5.293,5	3.828,6	1.465,0	0,11
	NAT	20.160,3	19.688,4	18.364,7	1.323,7	1.795,6	-471,9	-0,13
	WAT	2.484,5	2.214,9	1.754,7	460,2	729,8	-269,6	-0,64
	WET	1.163,3	759,2	255,0	504,1	908,2	-404,1	-2,34
Timișoara MA	ART	16.950,5	19.517,4	15.156,6	4.360,8	1.793,8	2.567,0	0,79
	AGR	196.695,9	194.288,3	189.218,0	5.070,3	7.477,9	-2.407,6	-0,07
	NAT	12.424,9	11.859,2	10.505,4	1.353,8	1.919,5	-565,6	-0,26
	WAT	476,7	2.500,6	382,1	2.118,6	94,6	2.024,0	9,65
	WET	2.946,1	1.328,4	914,4	414,0	2.031,6	-1.617,6	-4,33

The maps in Figures 3 and 4 provide a geographic visualisation of LULC dynamics across the Romanian MMAs, complementing the numerical data from the tables. These figures illustrate the spatial localisation of changes, offering important insights into the extent, distribution, and patterns of LUCC within and beyond metropolitan cores.

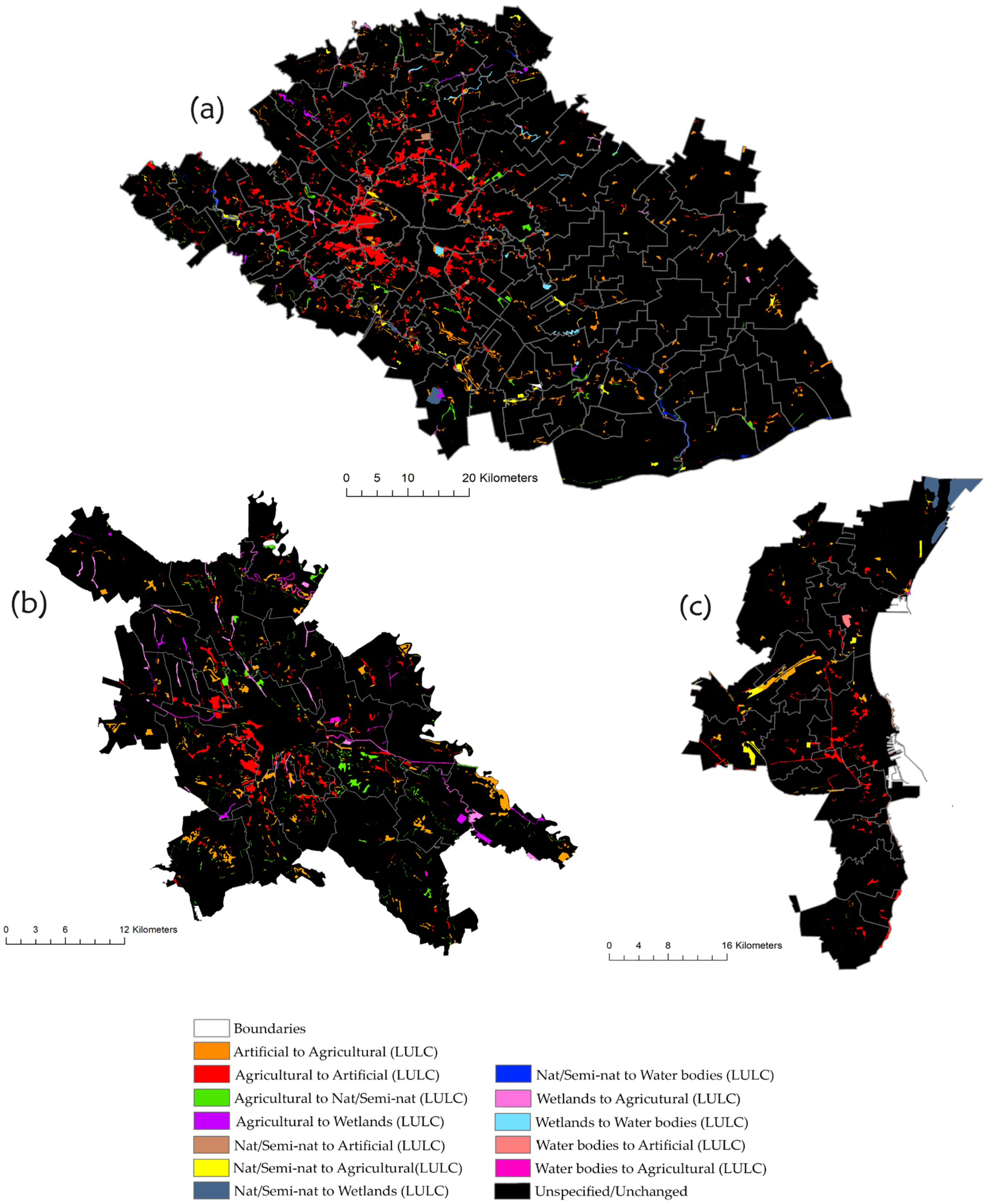

FIGURE 3. DETECTED LUCC IN: (A) BUCHAREST MA; (B) IAȘI MA; (C) CONSTANȚA MA

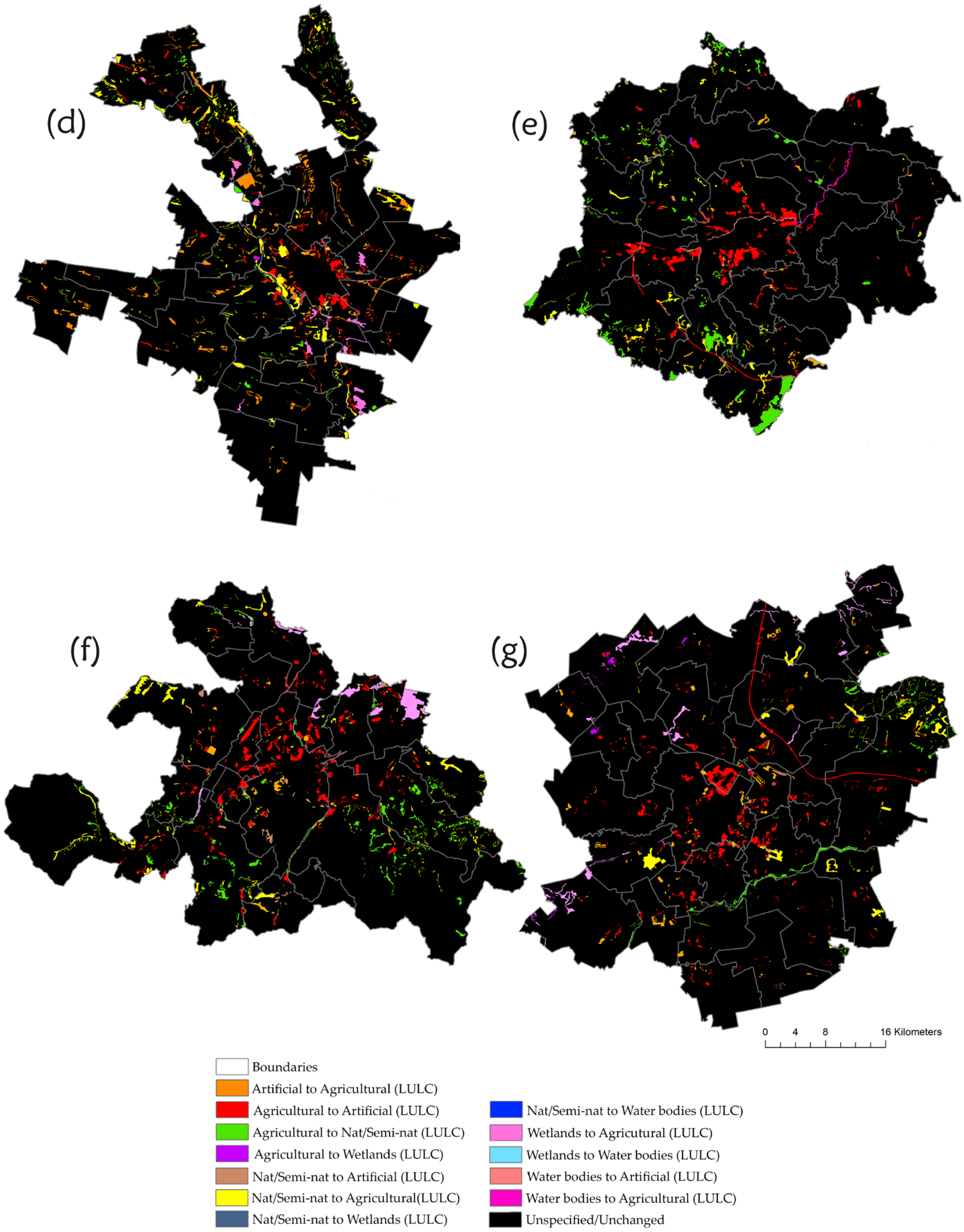

FIGURE 4. DETECTED LUCC IN: (D) CRAIOVA MA; (E) CLUJ MA; (F) BRAŞOV MA; (G) TIMIŞOARA MA

Bucharest's spatial patterns show a compact urban centre with major changes in the surrounding TAUs, indicating suburbanisation and urban sprawl, as presented in similar studies (Grigorescu et al., 2015). The outlying areas are distinguished by significant increases in artificial surfaces (ART) at the expense of agricultural land (AGR), indicating uncoordinated urbanisation. This emphasises the importance of integrated planning solutions for managing the fast expansion of peri-urban regions while mitigating their environmental implications. Similarly, Iași exemplifies a dual dynamic of urban densification and agricultural intensification in peri-urban areas, highlighting the intricate interplay between urban and rural land uses.

Constanța's coastal geography adds a distinct dimension to its LUCC patterns. The maps reveal a significant encroachment of urbanisation into ecological zones, while also highlighting localised restoration efforts. This juxtaposition underscores the delicate balance required between economic development and environmental preservation in coastal MAs, where natural ecosystems are especially vulnerable.

In the western MAs of Craiova, Cluj and Timișoara, diverse natural and socio-economic conditions shape LUCC patterns. Craiova exhibits a pronounced reliance on AGR as both an emitter and receptor of change, reflecting pressures from rural population density. Cluj and Brașov, restricted by their mountainous topography, exhibit more localised changes along accessible transit routes, emphasising geomorphology's effect on urban growth. Timișoara, on the other hand, shows strong ART increases associated with changes in wetland and water bodies, highlighting the difficulties of regulating LULC development in locations with sensitive natural environments. The patterns seen in the Timișoara MA offer additional layers of interpretation. For instance, the northeastern portion of the MA exhibits a clear linear transition from agricultural land (AGR) to artificial surfaces (ART). This line correlates to the completion of a relatively recent portion of the first highway in Romania, the A1, which is an important infrastructure development in the region. This linear transformation also serves as evidence of the reliability and precision of the model used to detect land-use changes, as it accurately captures and localises significant shifts linked to infrastructural expansion.

These spatial analyses enrich the article by providing a comprehensive understanding of the localised and broader geographic processes driving LUCC in Romania's MAs. The figures underscore the critical role of geography in shaping development patterns and highlight the importance of tailored strategies to address the diverse challenges posed by urban growth and land-use changes.

4. DISCUSSION

Results confirm that mainly the same drivers, in effect urbanisation and agricultural transformation are responsible for LUCC across Romanian MMAs. While local geographical and socio-economic factors introduce important variations, artificial surfaces (ART) expanded into the peri-urban rural areas because of urbanisation emerged as the most important driving factor across all MMAs.

At the same time, regional variables influence LUCC dynamics. For example, geomorphological constraints in Cluj and Brașov restrict urban expansion to accessible corridors, while high rural population densities in Iași and Craiova encourage agricultural intensification, not only urban sprawl. Environmental problems, such as the loss of wetlands and natural areas, highlight the competing strains of urban expansion and ecological preservation.

One of the study's notable findings is the unequal geographical distribution of LUCC impacts across MMAs. The urbanisation density in peripheral TAUs illustrates not only the propagation of urban pressures, but also the possibility of fragmenting peri-urban and rural environments. Measures that address the interdependence between large cities and their surrounding areas are necessary in light of this fragmentation, which has significant ramifications for territorial cohesion.

The environmental repercussions of LUCC, such as the loss of natural and wetland areas, indicate continued ecological deterioration that must be addressed by proactive conservation efforts. The observed patterns of wetland restoration in Constanța, albeit limited, show how tailored efforts might reduce some of these effects. These findings indicate that metropolitan management methods should incorporate environmental goals in order to maintain long-term sustainability.

The methodological approach brought into view not only the magnitude of changes but also their directional flows, such as shifts from agricultural to artificial land or from natural to artificial land. These methodological choices were very important for pinpointing general mechanisms that drive LUCC, as well as the local variability due to geomorphological and socioeconomic factors. The identification of broad tendencies, such as the dominance of artificial surfaces as receivers and agricultural land as emitters, supports the concept of similar processes driving change across MMAs. At the same time, the unique patterns found in areas such as Brașov, where geomorphological limits impact urban growth, and Constanța, where wetland modifications mirror coastal dynamics, emphasise the interaction of universal forces and regional circumstances.

The inclusion of additional statistical data helped to contextualise the spatial findings, offering insights into how demographic factors interact with LUCC patterns. This systematic methodology deepens the geographical analysis, offering a more nuanced understanding of how urbanisation processes and land-use shifts intersect in Romanian MAs.

The results presented in this study should be interpreted in light of the known limitations associated with the CLC dataset. Although higher-resolution alternatives such as Urban Atlas exist, they were not suitable for this analysis due to their limited coverage in later versions (2012 and 2018) and the lack of data for most metropolitan areas in earlier years. To improve the reliability of the dataset, land cover classes were restructured, and changes were cross-validated using high-resolution satellite imagery. Despite these efforts, the constraints of the CLC data remain and should be taken into account when interpreting the findings.

5. CONCLUSIONS

The meticulous processing and interpretation of CLC data and supplementary statistics have not only validated the study's hypothesis, but also demonstrated the importance of an integrated methodological framework for analysing LUCC. These methods strengthen, to some extent, the scientific basis of the results, offering valuable insights for metropolitan planning and sustainable development.

The results support the notion that, despite MAs' variety, common forces impact their spatial transformations. Understanding these principles, together with local variations, is critical for establishing adaptive metropolitan development strategies that balance urban expansion with sustainability.

Ultimately, the study's results demonstrate how the interplay of national and localised LUCC mechanisms shapes the spatial evolution of Romanian MMAs. This integrated understanding provides a framework for reconciling urban growth with sustainability goals, offering pathways for balanced development that respects both the socio-economic needs and ecological integrity of MAs.

Author contributions

Conceptualization: C.-A. Stoian, O. Groza; Data Curation: C.-A. Stoian, A. Sandu; Formal Analysis: C.-A. Stoian; Investigation: C.-A. Stoian, O. Groza; Methodology: A. Sandu; Project Administration: Not applicable; Resources: C.-A. Stoian, O. Groza; Software: A. Sandu, C.-A. Stoian; Supervision: A. Sandu; Validation: C.-A. Stoian; Visualization: C.-A. Stoian; Writing – Original Draft: C.-A. Stoian, O. Groza; Writing – Review & Editing: A. Sandu, C.-A. Stoian. All authors have read and approved the publication of the manuscript

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Conflicts of interest

The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AGR	Agricultural Area
ART	Artificial Area
CLC	CORINE Land Cover
EU	European Union
LUCC	Land-Use/Cover Change
LULC	Land-Use and Land Cover
MA(s)	Metropolitan Area(s)
MMA(s)	Major Metropolitan Area(s)
NAT	Natural/Semi-natural Area
NIS	National Institute of Statistics
TAU(s)	Territorial Administrative Unit(s)
WAT	Water Bodies
WET	Wetlands Areas

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