EDICIONES
COMPLUTENSE

Anales de Geografía de la Universidad Complutense
ISSN: 0211-9803

ARTÍCULOS

Large detail scale mapping from aerial orthophotos for understanding local-scale urban land use dynamics. The case of Madrid, Spain

Gabriel Gedda-Shaheen
Universidad Complutense de Madrid (Spain) ✉
Eduardo Caramés
Observatorio para una Cultura del Territorio (Spain) ✉
Jaime Díaz-Pacheco
Universidad de La Laguna (Spain) ✉
Richard J Hewitt
Instituto de Economía, Geografía y Demografía (IEGD). Consejo Superior de Investigaciones Científicas (CSIC) (Spain) ✉

https://dx.doi.org/10.5209/aguc.99038

Received: November 12, 2024 / Submitted for review: November 15, 2025 / Accepted: March 27, 2025 / Published online: July 18, 2025

Abstract. The Madrid Land Use project (MLU) is an aerial photographic interpretation-based mapping program for the Madrid region, Spain, now available for five time periods: 2000. 2006, 2009, 2014 and 2020. In this paper we showcase the most recent updates carried out by our team for 2014 and 2020. using examples from 10 municipalities in southeast Madrid, in particular, Arganda del Rey, Campo Real and Rivas-Vaciamadrid. The updated geodatabase enhances our understanding of urban development trends and land use patterns. Broadly, urban development followed a simplistic template initiated by the construction of road infrastructure, later infilling with multi-family housing, retail and facilities. This urban pattern is highly dispersed, increasingly car-dependent and energy and resource-inefficient, and thus not aligned with environmental, climate or sustainability goals. The results of the MLU show the continuing importance of large detail scale mapping from aerial orthophoto interpretation as an essential tool for understanding urban land use dynamics.
Keywords: land-use change; land-use map; photointerpretation; local-scale; land-use dynamics; urban development.

[ESP] Cartografía a escala de detalle a partir de ortofotografía aérea para comprender las dinámicas de los usos del suelo urbano a escala local. El caso de Madrid, España

Resumen. El proyecto Madrid Land Use (MLU) se dedica a la elaboración de una serie cartográfica de usos del suelo para Madrid, España, mediante interpretación de ortofotografía para cinco períodos de tiempo: 2000. 2006, 2009, 2014 y 2020. En este artículo se presentan las actualizaciones realizadas por nuestro equipo para 2014 y 2020. ilustradas con ejemplos de 10 municipios del sudeste de Madrid, concretamente Arganda del Rey, Campo Real y Rivas-Vaciamadrid. La base de datos actualizada mejora nuestra comprensión de las tendencias de desarrollo urbano y los patrones de uso del suelo. El desarrollo urbano siguió un patrón simple determinado por la construcción de infraestructura vial, que luego se completó con viviendas multifamiliares, zonas comerciales y equipamientos. Es un patrón urbano muy disperso, cada vez más dependiente del automóvil y energéticamente ineficiente y, por tanto, no alineado con criterios de sostenibilidad. El trabajo demuestra la importancia del desarrollo de productos cartográficos a escala detalle para comprender la dinámica del uso del suelo urbano.
Palabras clave: cambios de uso del suelo; cartografía de usos del suelo; interpretación fotografía aérea; escala local; dinámicas de uso del suelo; desarrollo urbano.

Cómo citar: Gedda-Shaheen, G., Caramés, E., Díaz-Pacheco, J., Hewitt, R. J. (2025). Large detail scale mapping from aerial orthophotos for understanding local-scale urban land use dynamics. The case of Madrid, Spain. *Anales de Geografía de la Universidad Complutense*, 45(1), 53-73.

1. Introduction

Recent decades have seen continuous evolution in the mapping and monitoring of Land Use and Land Cover Change (LUCC). In urban areas, databases developed for LUCC monitoring in multi-country regions have been criticized for their lack of detailed discrimination between different types of urban land use features, unsuitably small scales or large Minimum Mapped Units (MMU) (Díaz-Pacheco and Gutiérrez 2014; Lister et al., 2014; Muñiz and García, 2017; García-Álvarez, 2018). However, because of the substantial resource demand that large detail scale mapping of urban areas requires, in most countries, little has been done to remedy the situation. In some cases, excellent cartographic products are developed which are later discontinued when funding runs out. This is unfortunate because the value of a land use geodatabase product tends to increase over time as the recorded time series grows longer, as evidenced by the well-known and highly regarded CORINE land cover database series (Büttner, 2014; Dinç and Gül, 2021; Feranec et al., 2016). Nevertheless, discriminating between built-up areas dedicated to different purposes and showing how they change over time remains an essential task if we are to understand the evolution of urban land use patterns in cities. For many urban design and planning purposes, electoral districts provide too little information on the location of different land use activities (see, e.g. Hewitt et al 2024), while household level data, if available, is subject to statistical secrecy.

In this paper, we describe the development of a large detail scale land cover mapping exercise for Madrid, Spain. The Madrid Land Use (MLU) land cover map series was initially developed for the years 2000. 2006 and 2009, entering a hiatus after first publication in 2014 (Díaz-Pacheco and García-Palomares, 2014a). Subsequently, from 2021 onwards the series was updated to include the years 2014 and 2020. a process that we describe in this paper. This update was carried out by a new team, including some of the authors, using Geographic Information System (GIS) software and a variety of imagery sources.

We discuss the process of updating the MLU and show how the new five-period time series sheds new light on the development of peripheral districts adjacent to a large European capital city. In this sense, this paper can be understood as an extension of previous works discussing the process of creating the MLU and its utility in analysing urban growth patterns (see Díaz-Pacheco and García-Palomares, 2014a, b). Our work serves to emphasize the importance of continuously maintaining and updating low visibility but essential data products like MLU, at a time when scientific practice is strongly focused on automation (Artificial Intelligence) and pursuit of novel remote sensing approaches and products. Though we would not deny the great utility of these emerging technical innovations, we argue that careful, methodical mapping from high quality orthophotographs, together with a persistent approach to maintaining land cover map series over long time periods is of at least of equal importance to more fashionable automated approaches.

2. Research background: land use change in Spain

In Spain, land use patterns have undergone significant transformations over the past half-century, a period marked by profound political, economic, and demographic changes. These shifts reflect broader European trends but are uniquely shaped by Spain's socio-economic history, geographic diversity, and institutional policies. Historically, Spain has experienced intensified urbanization, agricultural land reorganization, and increased afforestation. These are processes often amplified by economic growth, internal migration, and changing consumption patterns (Delgado-Serrano and Hurtado-Martos, 2018; Serra et al., 2014). Key drivers of these changes include urban expansion, coastalisation, and rural abandonment, which together reshaped the dichotomy between urban and rural areas (Serra et al., 2014).

Between 1987 and 2011, the extent of artificial surfaces in Spain nearly doubled, as urban areas expanded, and industrial infrastructure tripled in size (Delgado-Serrano and Hurtado-Martos, 2018). Urban sprawl along the Mediterranean coastline and near major metropolitan centres like Madrid and Barcelona has been driven by demand for housing, tourism infrastructure, and an economic model that heavily emphasized construction until the 2007 financial crisis. At the same time, rural regions have faced depopulation and agricultural decline, with abandoned farmlands often transitioning into forested areas through natural recolonization or European Union policies like the Common Agricultural Policy (CAP). These trends have intensified irrigation systems in more viable agricultural zones while raising questions about the sustainability of Spain's land use (Delgado-Serrano and Hurtado-Martos, 2018; Serra et al., 2014).

The spatial and temporal complexity of these changes underscores the need for integrated approaches linking socio-economic trends with sustainable land management practices. Studies leveraging Corine Land Cover (CLC) data and multivariate statistical analyses highlight the critical role of governance and policy in shaping land use trajectories, offering insights into how urban-rural dynamics influence sustainability and territorial resilience (Delgado-Serrano and Hurtado-Martos, 2018; Serra et al., 2014).

This trend has been particularly pronounced in Madrid, the capital city, which has experienced substantial expansion. Historically rural, the Madrid region has transformed into a landscape dominated by low-density housing developments, transport corridors, and sprawling infrastructure, particularly during the late 1990s and early 2000s (Gutiérrez-Puebla and García-Palomares, 2008; Hewitt and Escobar, 2011; Díaz-Pacheco and García-Palomares, 2014b). Urban sprawl in the region has been characterized by dispersed residential growth, with urban patches expanding outward along road and rail networks. Studies by García Rodríguez and Pérez González (2002) and Aldana (2005) document this sprawl's alignment with the rapid decentralization of employment and population, particularly in the southern and eastern municipalities.

The peri-urbanization process has led to significant land-use fragmentation and reductions in agricultural and natural areas, with the Spanish Sustainability Observatory (Guaita et al 2008) highlighting the loss of semi-arid landscapes to artificial land cover. Between 1990 and 2000 alone, Madrid's urban land expanded by more than 30,000 hectares, with an annual growth rate of 4.77%, outpacing population growth (Hewitt and Escobar 2011; Díaz-Pacheco and García-Palomares 2014a). While much of this expansion occurred in dispersed residential areas, significant growth also occurred in industrial zones, primarily along major transportation corridors.

More recently, the 2007 economic crisis marked a turning point in the dynamics of Madrid's urban growth. Díaz-Pacheco and García-Palomares (2014b) observed a transition from chaotic, low-density sprawl to a more consolidated urban form emphasizing compact development and polycentric growth models. These trends have coincided with greater densification in suburban rings and the establishment of mixed-use metropolitan subcentres, a shift from the single-use developments that dominated earlier periods.

However, the shift from denser land use in older parts of the city to a more dispersed urban form, reminiscent of development patterns seen in the USA and Australia, raises concerns about environmental impact and sustainability, including increased reliance on private vehicles and greater ecological pressures (Hewitt and Escobar, 2011; Díaz-Pacheco and Hewitt, 2010). Landscape metrics reveal growing fragmentation of urban patches and heightened competition between urbanization and conservation efforts (Hewitt et al., 2020). Understanding these changes is crucial for local and regional governments as they plan for future development and address these challenges.

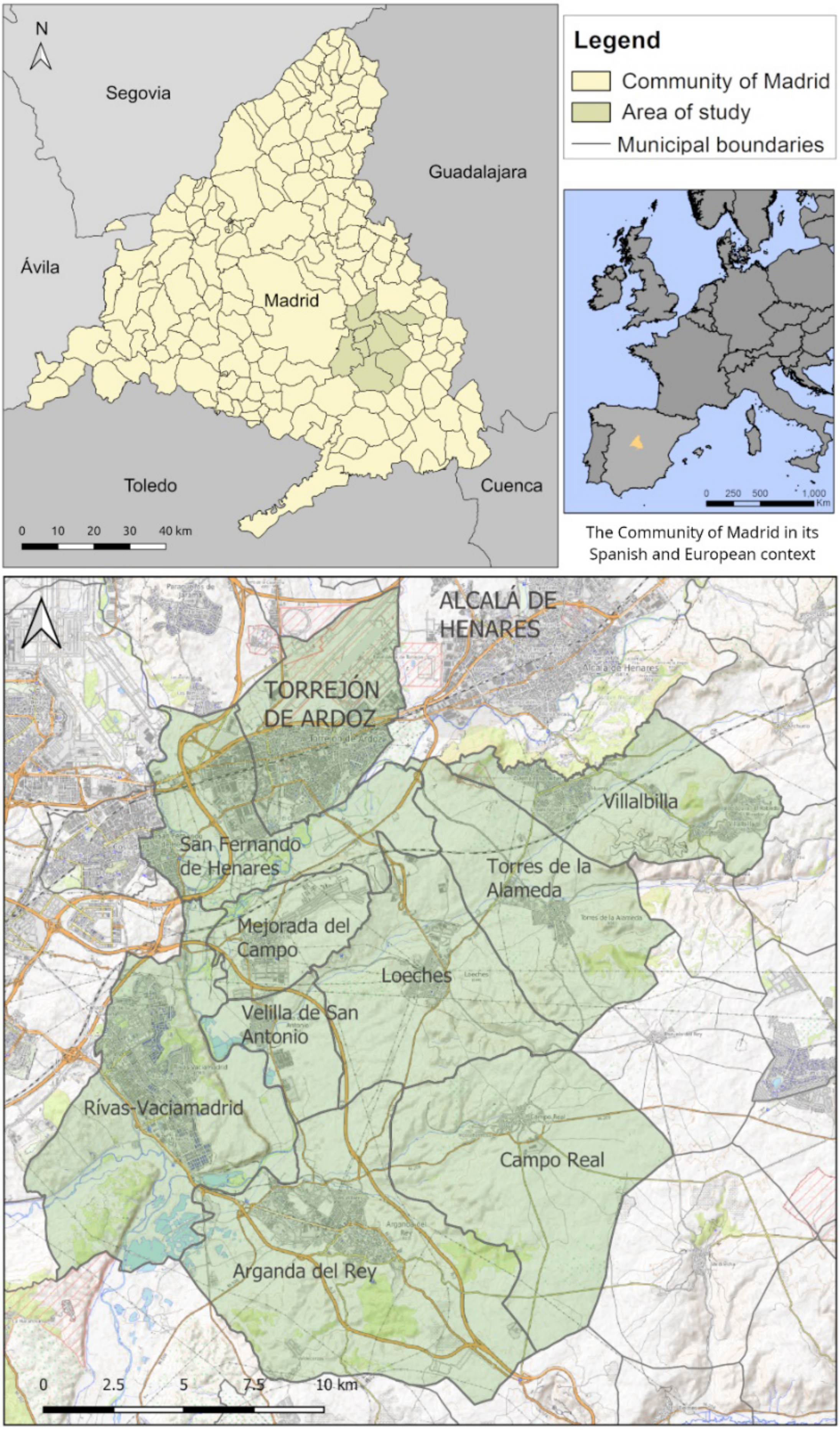
Quantifying and visualizing land use changes over time is essential for comprehending urbanization patterns. Land Use and Land Cover (LULC) geodatabases are created and updated regularly to provide detailed information that is spatially precise about land use (human use of land) and land cover (the physical state of the land) (Diaz-Pacheco and Gutiérrez, 2014). A prominent example of such a geodatabase is the European CLC dataset, which operates at a scale of 1:100.000 and categorizes LULC into 44 thematic classes (Büttner 2014). While CLC data has been useful for observing land use trends and supporting various studies that analyse environmental and socioeconomic issues, its quality and accuracy have limitations when compared to higher resolution LULC geodatabases, particularly for local approaches at larger scales (Diaz-Pacheco and Gutiérrez, 2014).

An alternative for more detailed regional studies is the Madrid Land Use (MLU) geodatabase, subject of the present article. MLU is a LULC database which was created to capture land use configurations in the Community of Madrid with high detail, focusing particularly on urban land with the intention of improving the attribute and position accuracy provided by CLC (Díaz-Pacheco and García-Palomares, 2014a). With a large scale of 1:10,000 and improved accuracy regarding specific uses, MLU is better suited for regional and municipal studies and planning compared to CLC (Diaz-Pacheco and Gutiérrez, 2014). MLU focuses exclusively on land use, without mixing land use and land cover (as in CLC), and is expressly focused on urban land uses broadly understood, whether in cities, towns or small villages. In MLU land parcels defined by plot divisions are assigned to a single majority use, rather than expressing a mixture of uses as proportions or percentages, as in SIOSE. The result is a detailed set of polygon layers that are usable in GIS software or convertible into raster images for various applications.

This study aims to show the patterns of development and urbanization over time in the Community of Madrid at a localized level, using the MLU geodatabase as a tool for visualization and quantification of land use. Though the land use map series has been updated for the whole Madrid region, in this study we focus on a group of ten municipalities southeast of the capital city of Madrid (Figure 1) in order to showcase the insights that can be gained from the large detail scale of the work undertaken, especially as a tool at the municipal level. The total area for the 10 municipalities is 435.5 km^2. Historically, these municipalities have been predominantly rural, reflecting the broader rural character of the country. However, rapid urbanization over the past few decades has transformed these areas and eroded their rural character, gradually (in some cases rapidly) integrating them into the expanding metropolitan area. Despite their varied development patterns, all these municipalities have undergone urban land use expansion due to their proximity to the capital. Many of them are now well-connected to Madrid via highways, the Madrid Metro, the Cercanías commuter rail service, or the intraurban bus system, effectively functioning as dormitory communities for the city.

Following this brief introductory section, we outline the methods and sources used to update MLU, and discuss in detail the composition, level of detail and expected accuracy of the geodatabase. Subsequently, we present the results and conclude with a discussion of the findings and their implications.

Figure 1. Study area, Madrid, Spain, showing the ten municipalities discussed in the paper.



Source: authors' own work with assistance from FA Pera. Open Topo Map and National Geographical Institute of Spain (IGN).

3. Materials and Methods

3.1. Sources

Several sources of information and materials were required for these updates. The main source for this study was the Madrid Land Use geodatabase for the years 2000. 2006, and 2009, which was to be updated for the years 2014 and 2020. This geodatabase served as an essential starting point, in the form of a polygon layer containing parcels and their land use categorizations under the Madrid Land Use categorization system for the three previously developed years. This system defines the use of each parcel in the geodatabase and is separated into 12 different categories, focusing on urban land use with an urban-nonurban binary. Table 1 shows these categories with their Spanish abbreviations (necessary to identify the uses in the GIS database).

Since the primary aim of the database was to provide an accurate and highly detailed record of urban land use types and their evolution, non-urban land uses were not specifically mapped and were instead included in the broad category "Unclassified" land. It is our intention to add updates to non-urban land use categories in future. Additional clarification for mixed or ambiguous land uses was provided, which will be detailed later.

Table 1. Madrid Land Use categories, with descriptions and examples.

Category	Abbreviation (Spanish)	Definition	Examples
Residential Multi-household	RM	Buildings in which several families live	Large blocks of flats, apartments, multi-story urbanizations, etc
Residential Single household	RU	Buildings in which the separation between family units is clearer	Terraced houses, individual homes. Dispersed low density urban developments, etc
Facilities (Educational)	EE	Facilities whose purpose is education	Schools, institutes, universities, environmental education centers, etc
Facilities (Health)	ES	Facilities dedicated to health. Private centers are not included.	Hospitals, clinics, doctors' surgeries, health centers, transfusion centers, etc
Facilities (General)	E	Facilities and buildings that do not fall into the educational and health categories	Cultural centers, religious installations, etc
Services	S	Similar to Facilities, but especially public administration or emergency services	Police stations, fire stations, civic centers, government offices, town halls, etc
Sports facilities	D	Facilities whose purpose is to carry out some type of sport or physical activity	Sports centers, tennis courts, equestrian centers, athletics tracks, stadiums, etc
Tertiary	T	Facilities dedicated to private business, retail and leisure	Theaters, cinemas, shopping centers, offices, etc
Urban Green Areas	V	Areas that are close to urban centers and are more open spaces do not have to be green "per se"	Parks, public gardens, wild land enclosed for public use, green corridors, etc. must be public.
Industry	I	Areas of industrial use – e.g. manufacturing, processing, or distribution	Industrial estates, industrial parks, factories, refineries, etc
Infrastructures	INF	Facilities, ways and routes dedicated to transportation, as well as the necessary buildings	Stations, roads, railways, airports, roundabouts, etc
Unclassified	SC	Land areas that do not fall into any of the previous categories	Rural land, crops, forest, natural areas etc

The work was carried out using QGIS for heads-up digitizing from aerial orthophotos and other information sources (see below), and for analyzing and editing the map layers. Digitizing tools like *Split Features* and *Fill Ring* were used to edit polygons, and the attribute table of the MLU layer was updated to record land use changes, such that all areas of the polygon coverage map had a designated single land use assigned to them, recorded in the relevant attribute column for each date (2000. 2006, 2009, 2014, 2020). Beyond the base map layer for MLU, other sources used were as follows:

- Madrid Municipalities Layer. A polygon layer of municipal borders named "Divisiones Administrativas de la Comunidad de Madrid", obtained from the Geoportal of the Community of Madrid (IDEM), was used to align the digitized polygons to exact municipal boundaries, avoiding generation of sliver polygons.

- Aerial images. Historic aerial photos from the Plan Nacional de Ortofotografía Aérea (PNOA) from the National Geographical Institute of Spain (IGN). For the years 2006 and 2009, PNOAs were accessed via a Web Map Service (WMS) from the IGN to save computer memory as they were only utilized when the downloaded PNOAs for 2014 and 2020 needed further confirmation.

- Google Maps. The plugin QuickMapServices was also used to add reference layers from Google to the project, including Google Labels and Google Satellite. Google Maps & Street View were used to provide street-level imagery to aid in identifying land use where aerial views were insufficient.

3.2. Criteria and procedures for updating the land use layers

To update the polygon layer for the years 2014 and 2020. specific procedures were followed to ensure accuracy and consistency in the MLU database. Initially, the PNOA layer for the year 2014 was made visible to observe the polygon layers accurately. The process of editing began by examining each parcel and its current designation to determine if any changes had occurred. If the land use remained unchanged, the corresponding category abbreviation was entered in the field for that year. In cases where there were changes in the use of the parcel but not its shape, the category abbreviation was updated accordingly in the relevant field. If there were changes to the use of part of the parcel, editing tools such as *Split Features* and *Fill Ring* were employed to reflect these changes without generating new polygons, but rather by dividing the existing ones.

When the land use was unclear from the PNOA images, additional resources like Google Labels were utilized to identify the building or land use. If ambiguity persisted or there were no labels, Google Street View was used to provide further clarification. The attributes and quality of the PNOA images varied year to year or by location, so past years' images as well as the current Google Satellite layer were used to help identify structures and their uses.

Non-built-up land was categorized as "Unclassified", a catch-all class encompassing various non-urban uses such as farms, orchards, forests, and fields. The explicit definition and inclusion of the unclassified polygons is an integral part of the database (rather than simply leaving non-urban parcels unmapped), since it allows non-urban land uses from other databases to be added later using overlay analysis techniques (e.g. zonal statistics, spatial join etc.). At present, the main interest and anticipated use cases for the MLU are urban, and detailed mapping of non-urban land use will be left for future work.

The focus was on classifying areas changed and occupied by humans for urban uses, allowing technicians discretion in categorizing certain outlying or ambiguous cases. In cases of doubt, technicians (9 in total, 2 or 3 each year between 2021 and 2024) sought clarification from the supervisory team and a classification was made jointly through a process of discussion and consensus. Further details on specific mapping procedure are given in Appendix 1.

Specific criteria were applied to certain land use categories. For Urban Green Space (V), some evidence of deliberate planning and the ability to travel on or through were required in order for a land parcel to be assigned to this category. Protected natural areas and unplanned green spaces (e.g. overgrown abandoned lots, vacant spaces between developments or awaiting developments) were excluded from this category. For Residential Multi-household (RM), if the ground floor had commercial uses (as is typical in many blocks in Madrid), it was classified as RM; however, if multiple commercial floors exceeded the number of residential floors, it was classified as Tertiary (T).

Some spaces posed classification challenges due to their multifunctionality or lack of specific characteristics. For example, "Centros de Convivencia", which are shared living spaces of various kinds (e.g. for unhoused or elderly citizens), or municipal spaces used for festivals or markets. In these cases, the classification used in previous years was maintained unless earlier classifications were obviously erroneous or a clear change in use was evident.

After these steps had been followed for a group of polygons, the 2020 PNOA was made visible, and the process was repeated section by section until the municipality was completed. By following these detailed procedures, the MLU database was accurately updated for 2014 and 2020. ensuring that land use changes were systematically documented and reflected in the GIS project. With a geodatabase containing the updated polygons and table with their categorization the next step was to create maps to visualize the land use pattern and changes over time and to extract the tables to quantify the changes. These maps included all 5 periods of the newly updated MLU database to give a more holistic view of how the areas have changed over time.

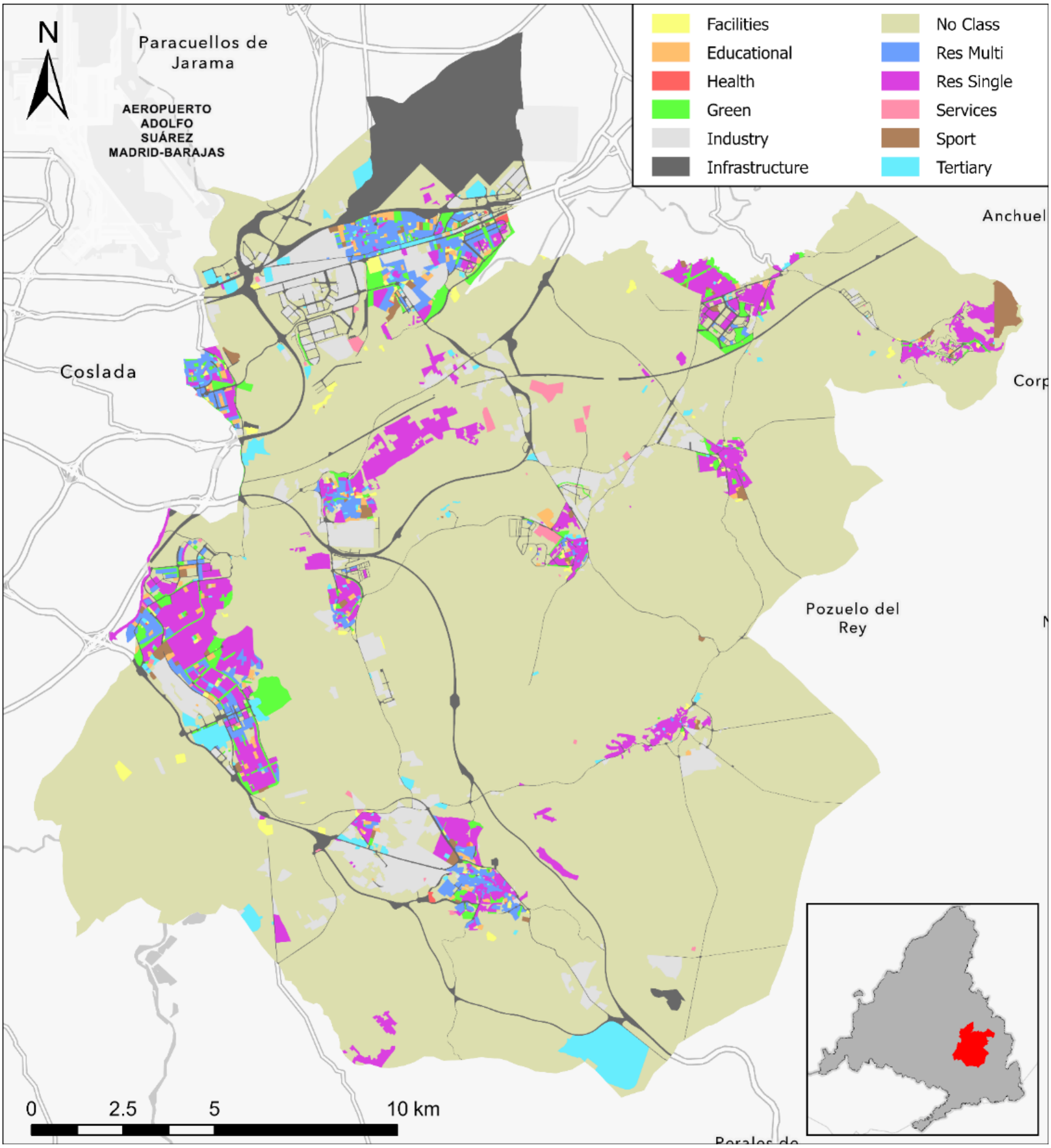
In order to highlight the specific patterns of development at the individual settlement level, which are important for understanding Madrid's ongoing development trajectory, and because detailed exposition and illustration of all ten municipalities would be repetitive and extend the article unnecessarily, we selected three of the ten municipalities described in this piece (Arganda del Rey, Campo Real and Rivas-Vaciamadrid) for detailed visualization and analysis. These three municipalities were chosen both for the large amount of change they had experienced and for the characteristic nature of their transformation, as representative of changes in the wider region. The cartography for this study was created using ArcGIS Pro, with the MLU polygon layers as the primary spatial data. The symbology of these layers was edited to ensure clarity, and the Layout feature was used to design and format the maps.

4. Results

4.1. Land use pattern of Madrid in 2020

The most recent MLU dataset from 2020. openly available at https://figshare.com/s/122f385b58094026f0a1, provides a detailed snapshot of land use distributions across the ten southeastern municipalities of Madrid. As illustrated in Figure 2, the study area consists of a combination of urbanized and non-urbanized (NC) spaces, with notable differences in development patterns between the northern and southern municipalities.

Figure 2. Land use in 2020 according to the MLU database for ten municipalities of southeast Madrid.



Source: own work.

The northern part of the study area includes the municipalities of San Fernando de Henares and Torrejón de Ardoz. These are part of an important industrial and infrastructure corridor following the Henares River, which flows approximately northeast to southwest from its source in the hills of the province of Guadalajara to meet the river Jarama at Mejorada del Campo in the province of Madrid. In this area urbanization is more continuous, largely driven by the Henares River industrial corridor and extensive transportation infrastructure. The municipalities in this area show a high concentration of industrial (I) and infrastructure (INF) land use, largely aligned with regional economic activity.

While the municipalities of the Henares River corridor in the north of our study area are increasingly interconnected by sprawling residential and industrial development, the three selected municipalities of Arganda del Rey, Campo Real and Rivas-Vaciamadrid in the south are for the most part distinct nuclei of urbanized land, interconnected only by infrastructure. These municipalities exhibit a more dispersed urban fabric, with urban centres interspersed among rural landscapes and agricultural zones. They are surrounded by rural land assigned to Unclassified (NC), which comprises the largest land use category, representing 78.19% of the total study area (Table 2). This category includes a combination of agricultural land, undeveloped plots, and natural areas.

Table 2. Percentage of area by category in 2020 for all the study area (ten southeastern municipalities) and the three selected cases.

MLU Category	All	Arganda del Rey	Campo Real	Rivas Vaciamadrid
Facilities	0.41%	0.39%	0.05%	0.49%
Facilities (Educational)	0.43%	0.27%	0.04%	0.74%
Facilities (Health)	0.04%	0.07%	0.00%	0.01%
Industry	4.66%	6.87%	1.66%	2.22%
Infrastructure	6.38%	3.47%	0.64%	2.40%
Residential Multi-household	1.79%	1.47%	0.03%	2.69%
Residential Single household	4.60%	3.48%	1.55%	8.98%
Services	0.28%	0.09%	0.04%	0.09%
Sport	0.50%	0.21%	0.04%	0.56%
Tertiary	1.41%	3.89%	0.09%	1.74%
Unclassified (NC)	78.19%	79.35%	95.83%	76.78%
Urban Green Space	1.33%	0.44%	0.02%	3.30%

The second largest land use category is Infrastructure (INF), accounting for 6.38% of the total area, largely due to the presence of the military airbase in Torrejón de Ardoz at the northern tip of our study area. The next most abundant category is industry, making up 4.66% of the land area. These industrial areas are typically located close to or adjacent to the urban nuclei and are not intermixed with other uses, forming single use "islands" of industrial use (*polígonos industriales*), a typical development model in Spain (Figure 3).

Another notable category is single-household residential areas (RS) (Figure 4), which constitute 4.6% of the total area, with notable concentrations in Rivas-Vaciamadrid and Velilla de San Antonio. As can be seen in Figure 2, the study area contains substantial amounts of land in this category, in some cases large contiguous blocks, in other cases with other land uses mixed within them. Multi-household residential areas (RM) (Figure 5), comprising 1.79% of the study area, are mostly confined to the urban core of the settlements, especially in the towns of San Fernando de Henares, Torrejón de Ardoz and Arganda del Rey. Despite the historic origin of these settlements, most of which were established villas by the 16th century, the large quantity of multifamily housing in the urban core reflects the more recent (later 20th century) densification and remodelling associated with the growing importance of the area due to its proximity to the capital. The three towns that were not significant independent settlements by the 16th century (San Fernando de Henares, Rivas-Vaciamadrid and Velilla de San Antonio) have all substantially outgrown their original core in recent times.

Figure 3. Polígono el Caballo in Loeches.

Source: Google 2025.

Figure 4. Single-Household Residential Street in Rivas-Vaciamadrid.

Source: Google 2025.

Figure 5. Multi-Household Residential Building in Arganda del Rey.

Source: Google 2025.

Smaller land use categories such as Tertiary (T), Urban Green Space (G), Sport (SP), and Services (S) contribute to the overall urban structure. Their distribution varies across the study area, with certain municipalities exhibiting higher concentrations based on local development priorities. These categories contribute to the mixed land use pattern that will be explored in the following sections.

4.2. Land use changes between 2000 and 2020

The analysis of land use in Madrid, with the new addition of 2014 and 2020 time periods to the MLU geodatabase, highlights significant land use changes across the ten selected southeastern municipalities of Madrid between 2000 and 2020. Table 2 shows the percentage area covered by each land use from 2000 to 2020 across the whole ten municipality area. Over these two decades, urban land use increased by 7.5%, directly corresponding to a decline in non-urban land, with the most significant expansion occurring between 2000 and 2006 (3.03%) and the smallest increase recorded between 2014 and 2020 (0.95%). The most substantial increase occurred in Infrastructure, which expanded by 1.76% over the study period, reflecting continued investment in transportation networks. Similarly, Industry increased by 1.26%, demonstrating sustained industrial development in the region. The Tertiary sector, which includes commercial and service-related establishments, grew by 1.25%, suggesting the continued inclusion of business and retail in the expanding urban landscape. Additionally, Residential Single-household areas expanded by 1.20%, in contrast to Residential Multi-household, which only grew by 0.69%. This difference signifies a potential rise in demand for single-household living but could also be attributed to the amount of land it takes up compared to denser, multi-household housing. While most urban categories exhibited growth, certain land uses fluctuated due to reclassification, updated data methodologies, and physical transformations.

Table 2. Percentage of area by category between 2006 and 2020 in the study area

MLU Category	2000	2006	2009	2014	2020	Change 2000-20
Facilities	0.40%	0.48%	0.56%	0.42%	0.41%	0.01%
Facilities (Educational)	0.28%	0.34%	0.35%	0.42%	0.43%	0.15%
Facilities (Health)	0.01%	0.01%	0.02%	0.04%	0.04%	0.03%
Industry	3.40%	3.87%	4.10%	4.32%	4.66%	1.26%
Infrastructure	4.62%	5.35%	5.36%	6.32%	6.38%	1.76%
Residential Multi-household	1.10%	1.43%	1.66%	1.69%	1.79%	0.69%
Residential Single household	3.39%	4.44%	4.71%	4.38%	4.60%	1.20%
Services	0.03%	0.01%	0.01%	0.20%	0.28%	0.25%
Sport	0.43%	0.52%	0.55%	0.48%	0.50%	0.07%
Tertiary	0.16%	0.19%	0.87%	1.32%	1.41%	1.25%
Unclassified (NC)	85.70%	82.67%	80.99%	79.14%	78.19v	-7.51%
Urban Green Space	0.32%	0.50%	0.56%	1.29%	1.33%	1.01%
Null	0.16%	0.16%	0.16%	0.00%	0.00%	-0.16%

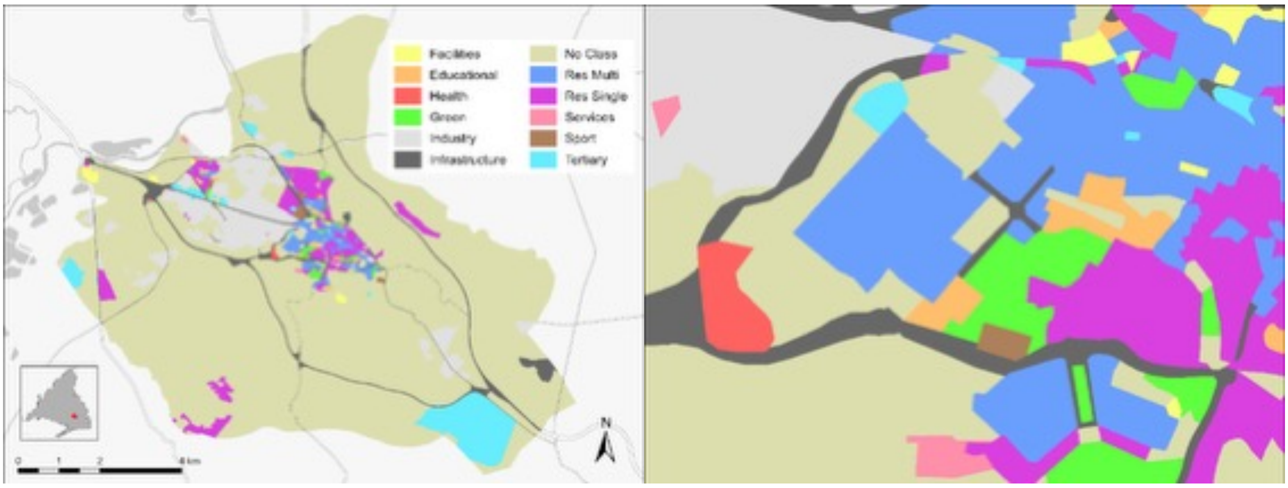
Between 2009 and 2014, several urban land use categories experienced declines. Facilities (general) peaked at 0.56% in 2009 but dropped to 0.41% by 2020. while Residential Single-household and Sport also saw reductions during this period, likely due to land-use transitions or changes in data classification methodologies. The most significant decline occurred in the Unclassified category, which fell from 85.70% in 2000 to 78.19% in 2020. a reduction of 7.51%, indicating the gradual conversion of previously undefined or non-urbanized land into classified urban uses. Additionally, the Null category, which accounted for 0.16% of land use between 2000 and 2009, disappeared entirely by 2014 due to refinements in data categorization.

Despite these fluctuations, overall urban land use increased, with several categories showing notable growth. In addition to the previously noted categories, Educational Facilities steadily expanded from 0.28% in 2000 to 0.43% in 2020 and the Sport category, although experiencing a temporary decline between 2009 and 2014, recorded a modest overall increase of 0.07%. One of the largest increases in urban land use was Urban Green Space, which grew from 0.32% in 2000 to 1.33% in 2020. underscoring an emphasis on recreational areas within the growing urban fabric. These broader trends in urban land use are also reflected at the municipal level, where individual cities have experienced distinct patterns of growth and transformation, which will be explored in the next section.

4.3. Land use pattern and changes in Arganda del Rey

The municipality of Arganda del Rey, situated to the south of the cluster of municipalities in the study area, has seen a significant population increase over the last two decades, from 30,662 inhabitants in 2000 to 56,678 in 2020 (INE, 2022). Arganda del Rey has a large, urbanized area in the north, with a mix of different land uses and a concentration of industrial land use to the northwest of the main residential population areas (Figure 6, left panel). Table 2 reveals that Arganda del Rey has 2.21% more land categorized as Industry, 1.16% more land assigned to Unclassified, and 2.48% more land classified as Tertiary than the study area as a whole. The large amount of tertiary land use can be largely attributed to the large zone in light blue in the south used for music festivals and other events. Infrastructure, although 2.91% lower than the total for the study area, crosses the whole municipality, connecting the main nucleus to surrounding settlements. A more detailed look at the urban core of Arganda in 2020 (Figure 6, right panel) reveals a large amount of single-household residential land in the southeast corner, shown in purple, bordered to the north by multi-household residential areas in blue, along with a mix of other land uses. The single-household residential land use is located in the older part of the town, with newer buildings being multi-household residential blocks. Comparison with the study area as a whole shows that this is a common pattern of development in this part of Madrid.

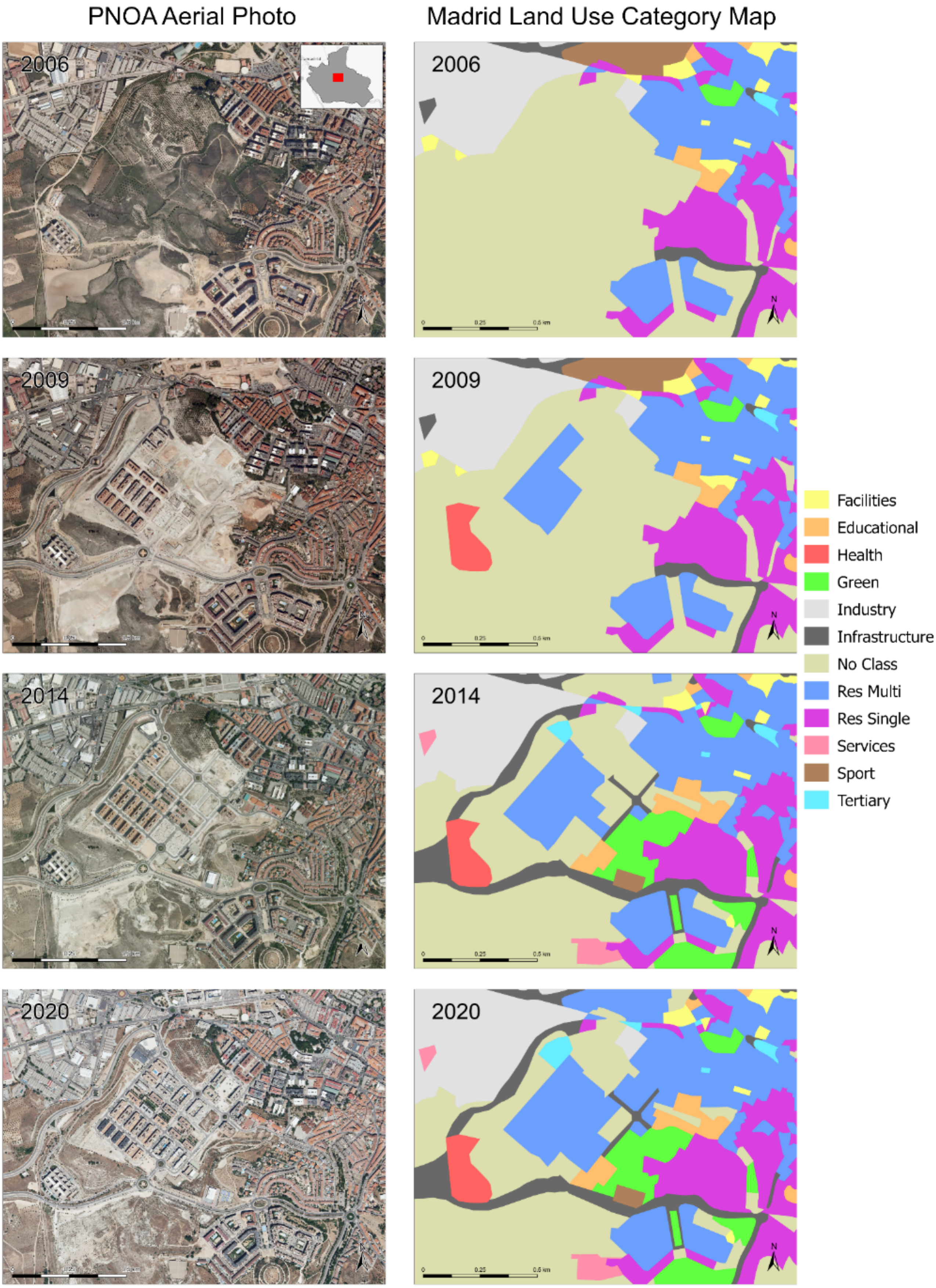
Figure 6. Land use in 2020 according to the MLU database in Arganda del Rey, Madrid. Arganda del Rey (left); detail of urban core (right).



Source: own work.

Figure 7 shows the progressive evolution of urban development of the core of the urban area, starting in 2000. with a PNOA aerial image of the zone on the left for the corresponding year and the MLU categorization map on the right. The centre and southwest quadrant are nearly all nonurbanized, assigned to the “Unclassified” category, but surrounded by urbanized zones with industrial buildings to the north and residential buildings to the east. By 2009, a road encircling the previously nonurbanized zone and the construction of a hospital and the first few apartment buildings in the centre can be seen. By 2014, more of the encircled area was urbanized with housing and more roads connecting it to the rest of the city to the north and east. By 2020. the formerly nonurban area is developed with multi-household dwellings and tertiary buildings.

Figure 7. Detailed comparison of land use changes from 2000 to 2020 according to the MLU database in Arganda del Rey, Madrid.

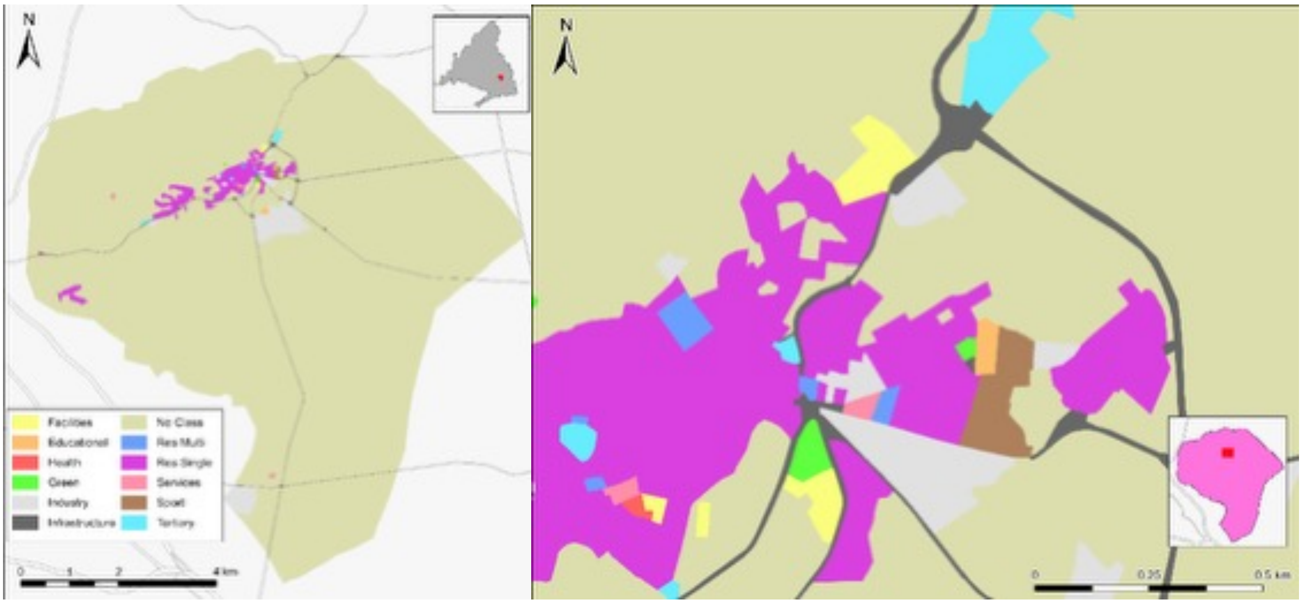


Source: own work.

4.4. Land use pattern and changes in Campo Real

The municipality of Campo Real is located east of Arganda del Rey and has seen its population more than double from 2735 in 2000 to 6420 in 2020 (INE, 2022). This smaller population is reflected in the much smaller urbanized area shown in Figure 8 (left panel). Table 2 shows that 95.83% of Campo Real is nonurbanized, categorized as "Unclassified". The urbanized nucleus is situated in the north, with Industry and Residential Single Household being the most prominent land uses, making up 1.66% and 1.55%, respectively. Infrastructures account for 0.64% of the total land use, connecting the urbanized nucleus to industrial zones in the south via a circular bypass (built *ca.* 2009) and linking the village to nearby settlements and major highways.

Figure 8. Land use in 2020 according to the MLU database in Campo Real, Madrid. Campo Real (left); detail of urban core (right).

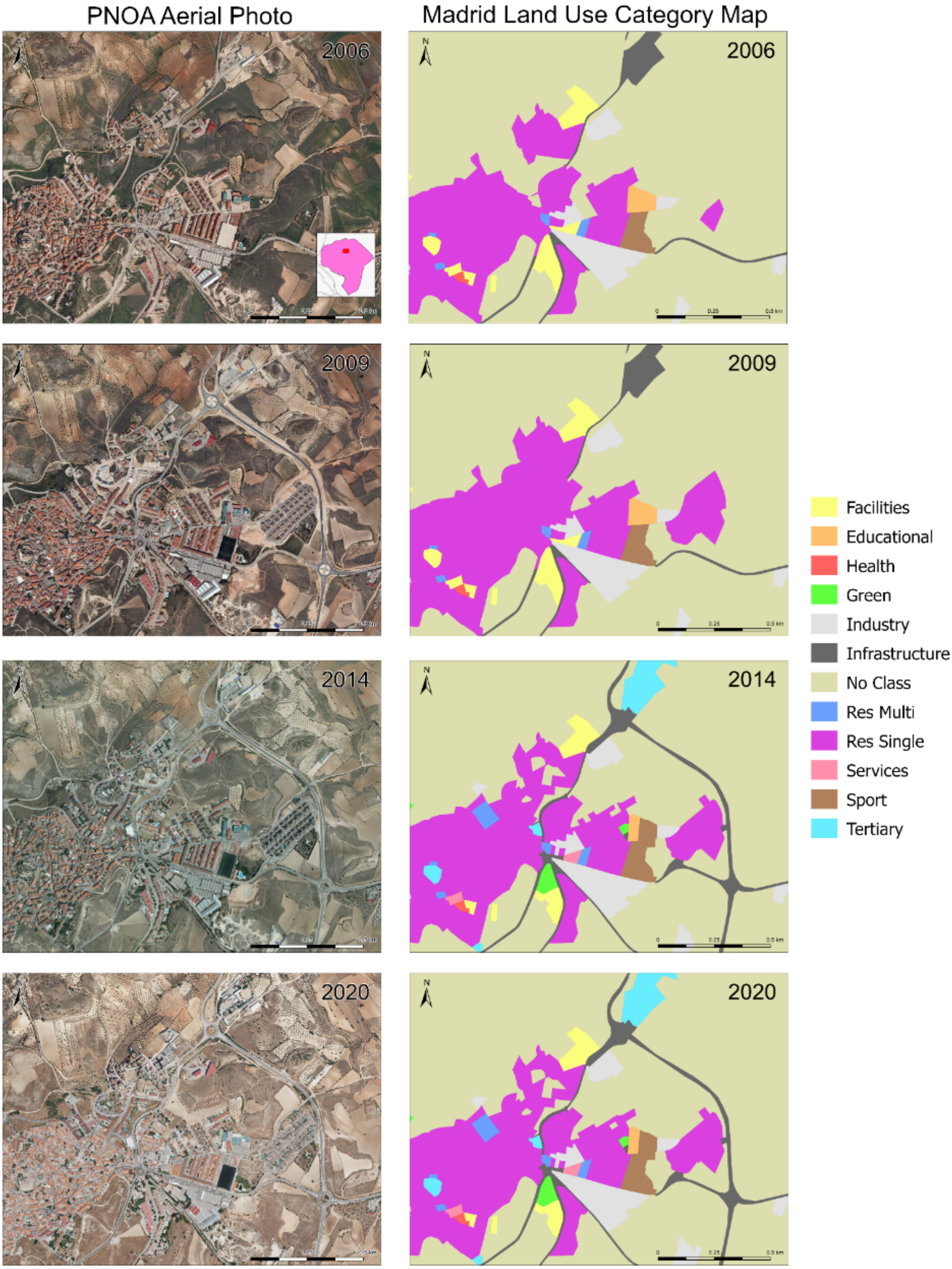


Source: own work.

Figure 8 (right panel) shows the urban core as mapped according to the MLU classification in 2020. The urban core comprises predominantly residential single-household land use, mostly in the older part of the town to the west. The eastern part of the town is more diversified with industrial areas, mixed facilities, and some urban green space, all connected by roads. The progression over time, shown in Figure 9, repeats a similar pattern to Arganda del Rey.

Beginning in 1999, the PNOA Aerial image in Figure 9 shows the older part of the city to the west, clustered around the church in a more organic street pattern characteristic of historic settlements, made up of mostly single-household residential buildings. At the northern edge of the historic settlement newer single-household buildings can be identified following a straighter pattern. By 2006 infilling has begun along the north and east boundaries within existing roads, and beyond the old town to the east around the school. Otherwise, the area to the east of the town is mostly nonurbanized with some smaller roads running through it. By 2009, two large roundabouts and a circular road bisecting the nonurbanized area and connecting the town to the industrial zone to the south have been constructed, and large planned single-household plots have begun to fill in the space between the road and the rest of the urbanized area. By 2014 this area to the east of the historic town is becoming increasingly built up with new residential developments. Little new development is observable between 2014 and 2020.

Figure 9. Detailed comparison of land use changes 2000-2020 according to the MLU database in Campo Real, Madrid.

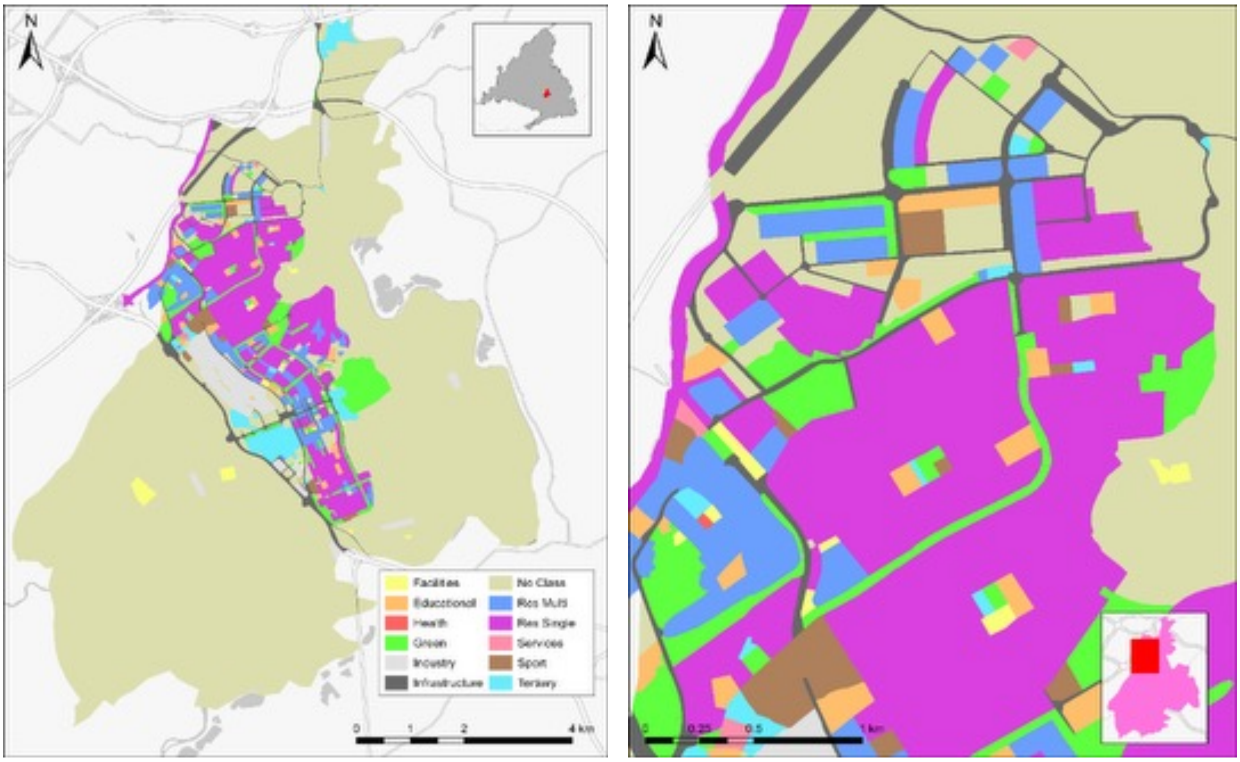


Source: own work.

4.5. Land use pattern and changes in Rivas-Vaciamadrid¡

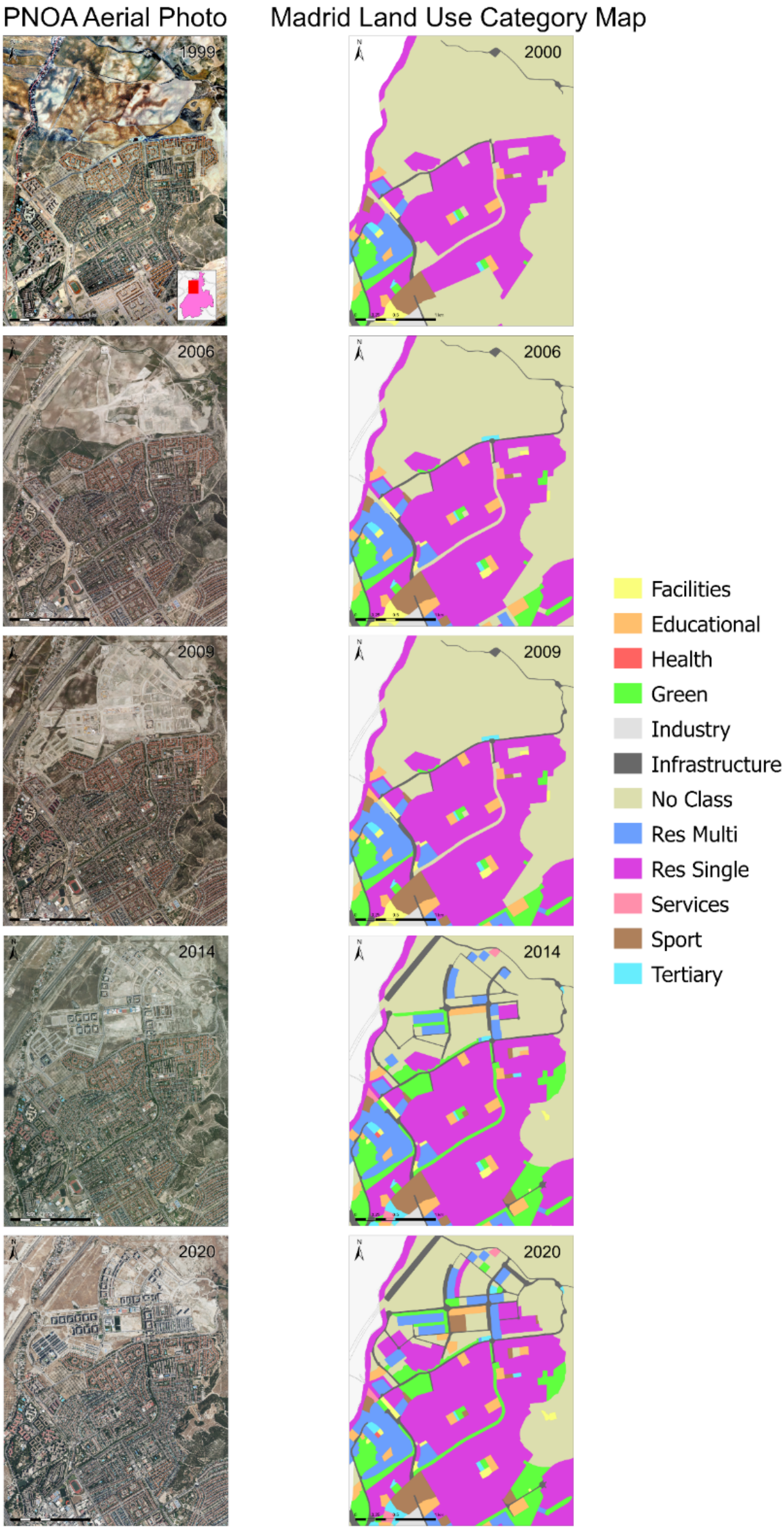
The last of the three municipalities of the study area selected for detailed discussion is Rivas-Vaciamadrid, which lies to the west of Arganda del Rey and borders the capital city of Madrid. It is the most populated of the three municipalities and has seen significant population growth from 29,092 in 2000 to 90,973 by 2020 (INE, 2022). As can be seen in Figure 10 and Table 2, a large area in the centre is classified as Residential Single household, constituting 8.98% of the total area, nearly twice as high as in the study area overall. Other notable land uses include Urban Green Space and Residential Multi-household, at 3.3% and 2.69% of the total area, respectively. The majority of land use is still classified as nonurban, with 76.78% identified as Unclassified, making up almost the entire southwestern half of the municipality. The urbanized core of the municipality is separated from its non-urban hinterland to the west by Infrastructure (2.4% of the total area), in the form of the A3, an important highway connecting Madrid with the coastal city of Valencia. Figure 10 (right panel) depicts the urban core in detail in 2020. This reveals a third, slightly different pattern of new single-household residential developments with mixed land uses, including Educational Facilities in orange, Urban Green Space in green, and connecting infrastructures.

Figure 10. Land use in 2020 according to the MLU database in Rivas-Vaciamadrid, Madrid. Rivas-Vaciamadrid (left); detail of urban core (right).



Source: own work.

Figure 11. Detailed comparison of land use changes from 2000 to 2020 according to the MLU database in Rivas-Vaciamadrid, Madrid.



Source: own work.

Examination of the evolution of the settlement over time (Figure 11) shows the extraordinary transformation that has taken place in this municipality, in which vast tracts of land to the north of the urban core in 1999 have been released for development, increasing the size of the town by 20% or more. The effect of the global financial crisis of 2007/8, and the subsequent severe recession are evidenced by the long delay in housing completions. This area, already laid out for development in 2006, remained unfinished in 2020. The modern town of Rivas-Vaciamadrid was developed after 1980 to the north of the original historic settlement oriented around the Plaza de la Libertad. As a result, the older, more organic development pattern seen in Arganda and Campo Real is scarcely in evidence.

5. Discussion and conclusions

The land use patterns observed in Madrid's southeastern municipalities mirror broader trends across Spain, where urbanization, infrastructure expansion, and agricultural decline have transformed territorial dynamics (Serra et al., 2014). Economic growth, internal migration, and policies such as the Common Agricultural Policy (CAP) have accelerated the conversion of rural land into artificial surfaces, promoting decentralized urban growth and increasing car dependency. While these trends have driven some economic expansion, they have also contributed to land fragmentation and inefficient resource use, raising long-term sustainability concerns.

Madrid, as Spain's capital, exemplifies these challenges. While its city centre remains compact and transit-oriented, surrounding municipalities are expanding through relatively lower-density development, where new road networks facilitate dispersed residential, commercial, and industrial expansion, particularly in Rivas-Vaciamadrid and Arganda del Rey. The direct role of transport infrastructures in driving urban growth in Madrid is evident in the proliferation of roads and the urban developments concentrated around them, in part due to the increased accessibility that these infrastructures provide (Gallardo and Martínez-Vega 2016). A combination of both the public investment in transport infrastructure and the social trends favouring suburban, segregated residential communities (Fernandez and Creutzig, 2016; Díaz Orueta, 2007; García-Palomares, 2010) has arguably shaped the land use patterns observed in this study. While our primary focus has been on land use transformations, future research could further explore the interplay between transport accessibility and urban expansion, integrating mobility network data to better understand these dynamics.

This shift away from traditional, walkable urban forms reinforces car dependency and strains public services. Addressing these issues requires a transition toward compact, well-connected urban planning. The MLU geodatabase provides a critical tool for monitoring these changes, offering valuable insights to policymakers seeking to balance urban growth with sustainability objectives.

5.1. Madrid Land Use in comparison with other land use products

With a nominal scale of 1:10,000. the MLU project geodatabase represents the largest freely accessible and easy-to-use off-the-shelf detail scale mapping for urban areas for the community of Madrid, and, with the update presented in this paper, is now available for the years 2000. 2006, 2009, 2014 and 2020.

The updated geodatabase, thanks to its large scale and specific focus on urban areas provides a more accurate and reliable frame of reference for the analysis of local scale urban land use dynamics than CLC (Diaz-Pacheco and Gutiérrez, 2014; Díaz-Pacheco and García-Palomares, 2014a). However, since development of the initial series of MLU land cover maps some alternative products have become available which merit brief attention here.

The first of these is the national land cover dataset SIOSE (officially the Land Cover Information System for Spain) of the National Geographical Institute (IGN) (Valcarcel et al. 2008). Since 2012, CLC for Spain has been obtained directly from SIOSE; however, the generalization process used to move from SIOSE to CLC is known to introduce error (García-Álvarez, 2018). SIOSE, in general terms, is likely to perform better than CLC for analysis at detailed scales, since its smaller minimum mapping unit (0.2–2 ha for SIOSE; 25 ha for CLC) means that patch level definition is finer (more and smaller polygons), meaning a better detection rate for smaller changes (García-Álvarez, 2018). Nonetheless, SIOSE is not an easy product to use, since land uses are not defined using a hierarchical system in which broad generic composite coverages are defined. Instead, the dataset provides for each polygon the percentages of the different uses and covers that contribute to its composition. For example, a low-density residential area with a house, garden, access road and a swimming pool might be recorded as being composed of 50% housing, 15% road surfaces, 15% trees, 15% herbaceous vegetation, 5% artificial liquid (Valcarcel et al. 2008). This limits the usefulness of the dataset for detailed mapping, since what is usually required is a simple assignment to the most important land use class within a given plot (Díaz Pacheco et al., 2018). This can be obtained by writing a script program to assign the category with the largest percentage to the polygon, but this is a time-consuming and imperfect solution. MLU, which directly assigns each plot to a single category, is easier to use in this sense, and, at 1:10,000 scale, also offers more detailed depiction of urban land uses. The SIOSE AR (high resolution) database is a more detailed product which may address some of these difficulties, and, at a scale of 1:1000-1:5000. Unfortunately, it is currently available only for the year 2017, meaning temporal evolution of land use changes cannot be analysed.

The next land use geodatabase that is of interest here as a point of comparison is the official land cadastre operated under the remit of the tax office (hacienda), which has lately become available for download in GIS format. The land cadastre offers very detailed land use classification at the parcel level (1:500-1:1000 in urban areas, 1:2000-1:5000 in rural areas) and, as the official source of land use information maintained by the state for tax purposes, is the preferred source for studies of urban land use mix at the local level

(García-Álvarez 2024). Nonetheless, due to the complexity and quantity of information available, processing the land cadastre to obtain a land use polygon coverage is not a straightforward process. The easiest way to obtain usable GIS data is through the Inspire Catastral Downloader QGIS plugin developed by Soriano (2023), which produces building level polygon data under a 6-level land use classification. For more detailed classification, the Cadastral Classifier plugin developed by Shurupov et al. (2023) can be used. Thus, while the land cadastre is both more detailed and more accurate, MLU again offers a simpler solution, especially for multi-year comparison.

5.2. MLU and the evolution of local-scale urban land use dynamics

The process of geodatabase development outlined in this article provided the opportunity and impetus for a detailed examination of settlement pattern and evolution of a cluster of smaller settlements in an area near to the Spanish capital, within a heavily urbanized and increasingly densely populated region. These peri-urban municipalities provide insight into how the Madrid region is growing through a process of dispersed urban and infrastructure expansion into formerly rural areas that, while often lacking in spectacular landscape character of the sort typically thought to merit protection, are part of a larger territory of considerable ecological and landscape value (Hewitt and Escobar, 2011; Díaz-Pacheco and García-Palomares, 2014). The study area, despite the enormous growth we have documented here, is almost 80% nonurbanized. However, as Figure 2 shows, much of the study area is cut up into multiple pieces by infrastructure, in particular roads and railways, disrupting and fragmenting the continuous quality and large open spaces which were once so characteristic of this part of the region. These individual segments or pieces into which the territory has been cut are gradually shrinking as once isolated settlements sprawl outwards with low-density residential areas, industrial zones, schools, hospitals, sports and leisure facilities, eventually connecting with neighbouring towns, facilities and infrastructures.

This pattern of expansion and urbanization was demonstrated by the three municipalities chosen as foci for this paper, all of which experienced significant population growth in the last two decades and have expanded their urbanized areas. In the first, Arganda del Rey, the built-up area was a combination of older single-household development and newer single and multi-household developments with other land uses mixed in. The municipality also had a larger area of industrial land compared to the region as a whole, at the edge of the town and linked to the residential areas by roads. The pattern of new development which seems to be typical for the Madrid region as a whole was first observed here, with the infrastructure (mainly roads) encircling an area that is mostly nonurbanized and then slowly, or rapidly in some cases, being infilled with apartment buildings, single-family homes, shops, offices, schools, and other uses.

The second municipality, Campo Real, was different in form, with almost 96% of it being nonurbanized and a much larger proportion of the urban core being composed of older organic development and single-household buildings. However, the pattern of recent development was similar to Arganda del Rey and the other municipalities of the study area with a large number of infrastructures that cut up the nonurbanized areas in smaller parcels. Just like Arganda, in Campo Real a new road was laid out encircling the northeastern area of the settlement, which was then gradually infilled with planned car-oriented development, including many single-family homes.

The third and final municipality was Rivas-Vaciamadrid, which had much more single-household development, a tightly planned design, and slightly less nonurbanized area compared to the other municipalities. The municipality still retains around 77% of the area undeveloped, but the sprawling urbanized nucleus is slowly expanding into this space. The new development in all three of the municipalities includes many components of New Urbanism (Fulton, 1996), such as mixed use, green spaces, and biking and walking paths. Despite this, the development is still heavily car-oriented, with large roundabouts, driveways, and garages for most of the new single-household units built.

The development patterns shown by the maps have a recurring theme of encircling nonurbanized natural areas with car-oriented infrastructure and then filling them in with relatively lower-density development, including many single-family homes. While it is true that the development is still relatively dense compared to the American model of sprawl (Ewing, 1997), it greatly diverges from the ultra-walkable urban centre of the city of Madrid and the country's historic towns as a whole. Further widespread urban expansion in the region would seem to be inevitable as the population trend continues upward. However, the strongly car-oriented, sprawling development template evidenced by the analysis presented in this paper should not be accepted without challenge. As settlements grow, especially in the context of severe ongoing climate change, which presents serious challenges not reflected in existing regional development models (Masselot et al., 2023), the region deserves better than a spaghetti-tangle of highways, big box stores and cheaply built identical blocks (Brody 2013). Though the larger houses, new hospitals, schools and sports facilities are welcome, the proliferation of low-density suburbs comes at a cost, with economic activity frequently displaced to out-of-town malls (Gerlofs, 2012). Under this model, the much-celebrated 15-minute city (Pozoukidou and Chatziyiannaki, 2021) becomes unattainable as giant retail parks spring up on the ring roads, small city centre shops close down, and citizens have to get into the car to make all of their purchases (Talen and Jeong, 2019). Though much of the traffic flow to and from malls on the circular roads relates to the dynamics of commuting, some of the largest single-use residential developments lack walkable access to shops. This model of development may also have less tangible, though no less important implications. There is some evidence to suggest that citizens' emotional place attachment is more strongly linked to the historic buildings of the core city (Hewitt et al 2020), rather than to the outer areas. In this sense, a sure way to destroy both the vibrant economic activity and place-identity of a historic town is to encircle it with low density suburbs. These aspects deserve much more attention than they currently receive, as local leaders and planners create their plans for their cities. Tools such as the Madrid Land Use geodatabase are important to show how development and urbanization are occurring at regional and local levels, and as such, have an important part to play in developing more sustainable, liveable cities.

Data availability

The full Madrid Land Use (MLU) database is available at: https://figshare.com/s/122f385b58094026f0a1

CRediT authorship contribution statement

Gabriel Gedda-Shaheen: Formal analysis, Investigation, Visualization, Writing – original draft. Eduardo Caramés: Data curation, Methodology, Supervision, Writing – review, and editing. Jaime Díaz-Pacheco: Conceptualization, Methodology, Writing – review, and editing, Richard J Hewitt: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Writing – review, and editing.

Acknowledgements and conflict of interest statement

The work described here was initially developed under the European Union funded project INTRANCES (Ref 886050) and continued under a Ramón y Cajal Research Fellowship award (IMOSET project) from the State Research Agency (AEI) of the Spanish Ministry of Science and Innovation (MCIN) 10.13039/501100011033 through the "ESF Investing in your future" funding framework. Richard J Hewitt also gratefully acknowledges funding provided under the FUTUREGREEN project, reference PID2023-152776OB-C21, by MICIU/AEI /10.13039/501100011033 and by FEDER, EU. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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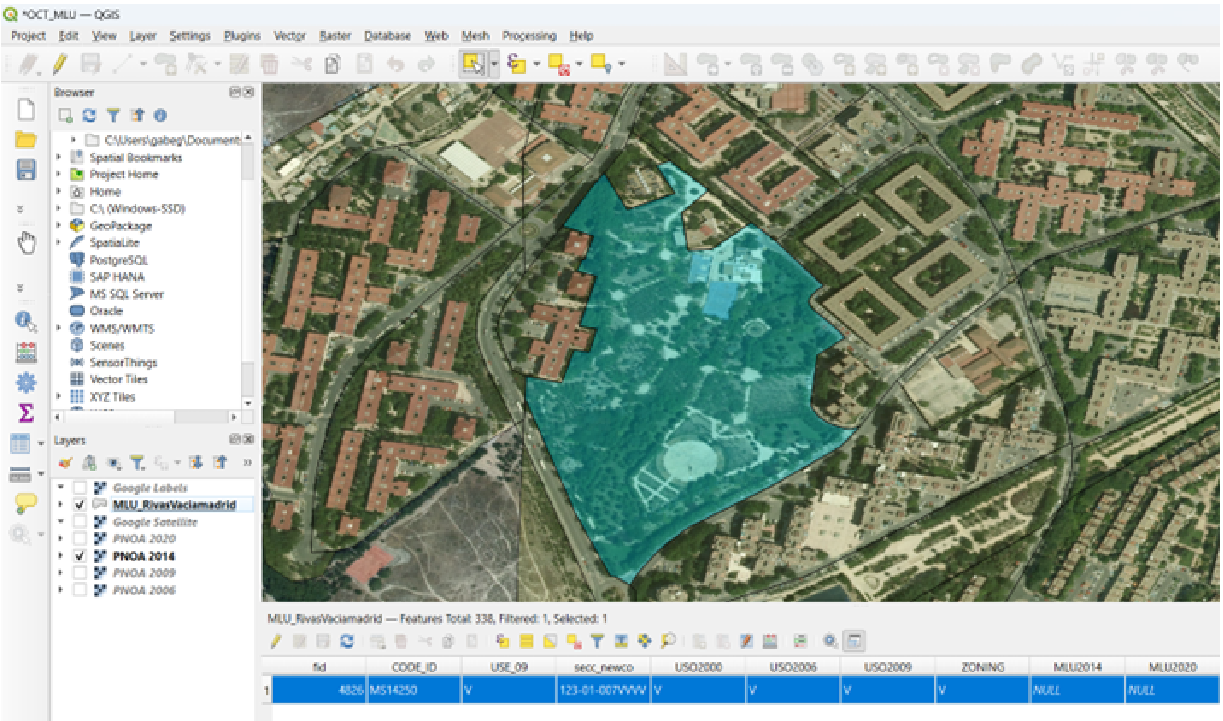
Appendix 1. Mapping procedure and preparation

The Madrid Land Use (MLU) database updates for the years 2014 and 2020 were carried out simultaneously, an approach we recommend so that complete time series become available in specific locations piece by piece. This is useful for projects such as MLU, which are undertaken by multiple technicians working on different non-overlapping areas at different times. Though the approach admittedly risks introducing discrepancies between areas mapped by different technicians, simultaneous mapping of several dates encourages individual technicians to maintain coherence across dates, something that is otherwise difficult to do in ambiguous cases (e.g. on distinguishing between services and different types of facilities).

The process was carried out in QGIS software, in the following way: first, the QGIS program was launched, and a new project was created. This initial step sets up the workspace for the subsequent tasks. Next, the necessary layers were added to the project (Add Layer -> Add Vector Layer): first the Madrid Land Use "Digitalizar" Geopackage followed by the Madrid Municipalities layer.

This process was repeated for the aerial images provided by the Plan Nacional de Ortofotografía Aérea (PNOA). Images for 2014 and 2020 had been downloaded and were added directly as raster layers. The 2006 and 2009 images were added by creating a new Web Map Service (WMS) layer using the URL provided by PNOA and then 'Connect' to display the available layers. The desired layers were selected and then 'Add' was clicked to integrate them into the project (Figure A1).

Figure A1. Screen Capture showing mapping work in progress in QGIS in the municipality of Rivas-Vaciamadrid



Next, the QuickMapServices plugin was installed. To add layers using the plugin, we used the 'Get contributed pack' option from the 'Settings' menu (Settings -> More Services -> 'Get contributed pack). 'Google', and 'Google Satellite' and 'Google Labels' layers were added in this way. These layers provided additional reference points crucial for detailed inspection required to correctly classify the land parcels.

The next step involved selecting the specific municipality to work on. This was done by clicking on the Madrid Municipalities layer in the 'Layers' panel and using the select tool (represented by a yellow square icon), to choose the desired municipality from the map. Keeping the municipality selected, the 'Select by Location' tool was used, setting the parameters to select features from the MLU polygons layer that intersected with the selected municipality, followed by clicking 'Run' to perform the selection. Once the MLU polygons were selected, the features were exported as a new geopackage with the name of the municipality. Following this, the symbology of this new layer was modified to enhance visibility by using rule-based filters to keep unchanged parcels transparent, and to increase the opacity of the finished ones.

To facilitate easy access and editing, the attribute table for the new layer was opened and docked to the bottom of the QGIS window to ensure it remained in view and 'Show selected features' was then clicked to focus on the polygons being worked on. In the attribute table, editing mode was toggled on and new fields were added. These new fields were named 'MLU2014' and 'MLU2020', with the field type set to 'Text.'

Finally, snapping was enabled to ensure precision in editing. This was done by clicking the 'Snapping' toolbar (represented by a magnet icon) and setting the snapping options to vertex and segment, ensuring the vertices and edges of the polygons were accurately edited. By following these comprehensive steps, the GIS project was set up, all necessary layers were integrated, and the workspace was prepared for detailed inspection and mapping of land use parcels and changes over the time period of interest.