Chapter 16
Urban Regions Under Stress: The Case of Madrid After the Lockdown

J. Barros-Guerton and J. M. Ezquiaga-Domínguez

Abstract Urban density, mobility, and revenue disparity are relevant factors in terms of urban analysis and project. The COVID-19 pandemic declared in March 2020 has meant a stress test for urban regions, as the alteration of mobility patterns led to changes in social dynamics. This paper investigates the correlations between the evolution of the disease and these three factors. The analysis focuses on the Madrid Urban Region, in Spain, and uses open data available from cadastral, census, and health-related official websites. This use of public information also provides a test on how such inputs could fit in a regional digital twin and can help replication. The analysis shows that overall, the basic structure of regional urban centralities, those with more people at day than at night, keeps stable in the central city and relevant economic areas. There are signs of temporary relocations to low-density areas, to holiday homes, which decreased in 2021. And there is no mathematical correlation between density and disease at the end of the period; figures show, however, of significative correlation during the initial stages, so density, at the household level (housing overcrowding) more than at the neighborhood level (dwellings per hectare), appears as an initial driver for disease expansion whose influence has been dampened progressively over time.

Keywords Resilience · Urban regions · Madrid · COVID-19 · Urban density · Open data

16.1 Introduction

Cities, and urban regions as well, are organizations that over time have evolved to cope with changes in their context. Changes have been a constant in history, and over the recent few years, there has been an increase in their speed due to the geopolitical context and the pressure that climate change is placing on the resources that urban

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dwellers use. The concept of resilience as the ability of a system to recover from difficulties has become relevant to cities and territories, and the COVID-19 pandemic provides a testing ground of interest. The recently published articles of Wang et al. (2022), Zidong and Liu (2022), Esteban y Peña et al. (2021), Carozzi et al. (2020) and Instituto Nacional de Estadística (2022c) show examples of attempts to get knowledge from the pandemic, as well as the complexity of the task. The work of Batty (2017) provides a wider view on the need to integrate approaches to define a new science of cities integrating all that knowledge, and the surge in open data availability provides an opportunity for study.

16.2 Background

Urban density has been one of the main indicators in urban planning since its modern formulation. Since the COVID-19 pandemic began, voices in the press like Rosenthal (2020) or Gracia (2020) have argued that cities, as dense concentrations of population, are natural hotspots for the illness. The knowledge acquired over the last 3 years provides a longer perspective to evaluate the links between density, mobility, and health. The case of Madrid is well suited for such an analysis due to its five million population and rich public open data landscape.

The COVID-19 pandemic has been a major stress factor for most cities globally. In Spain, the first case of the disease was confirmed on January 31, 2020, and on March 14 of that year, a lockdown was enacted by the national government. The government lifted gradually this lockdown starting in May, allowing short strolls around homes, until June 21, 2020, removing mobility and travel restrictions, while indoor capacity restrictions for retail and hospitality businesses along with mask use have remained longer.

During 2020 and 2021, the regional governments have defined territorial mobility restrictions in areas where the incidence rate has been higher. In Madrid, restrictions used the basic health zones, a territorial subdivision which establishes the public basic health center that corresponds to each citizen. Residents in zones with high incidence rates were allowed to go to work and essential chores, resulting in more mobility freedom than during lockdown, but were not allowed to move for less stringent uses. As the dense city is subdivided into many adjacent basic health zones without physical barriers, and the basic health zones subject to restriction were updated frequently, there has been a real difficulty in communicating those perimeters to citizens in a comprehensible way and to enforce effectively those measures in a city with a high percentage of pedestrian mobility, so this has not been considered in this article.

The impact of the pandemic on the Spanish economy in general, and in the Madrid Region, has been quite high, as tourism, one of the main revenue sources, has been sharply reduced for almost 2 years. Although there has been a rise in telecommuting for those jobs able to use those technologies, unemployment increased and specific brief time working strategies were widely used to cushion the impact of the crisis on the society.

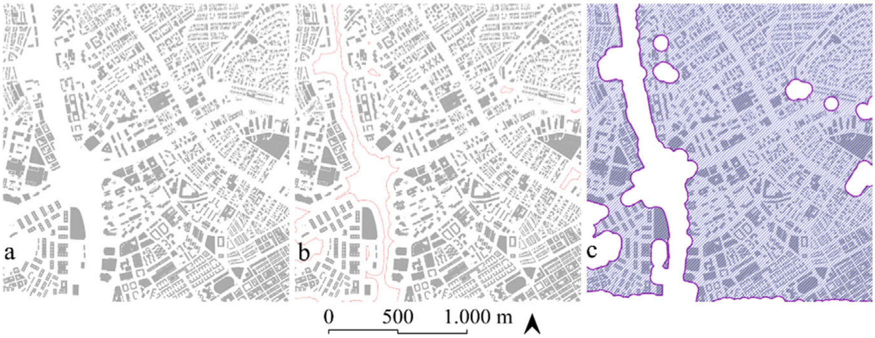


Fig. 16.1 Homogeneous area measure geometric definition, from building footprints (**a**) through a first outward 50 m buffer (**b**) and a further inward 50 m buffer (**c**) of the resulting polygons (*Source* authors, 2022)

16.3 Methodology

16.3.1 Case Study Selection

The urban region of Madrid, which for the purposes of this study we consider as a working simplification as equivalent to the political region of the Comunidad de Madrid, covers an area of 8.030 km^2 and has a population of over 6,7 million. Along with the city of Madrid, which acts as the core of the region, there are also high mountain ranges and rural areas which are sparsely populated. Due to its size, the region presents a diversity of physical, social, and economic contexts which facilitate a comprehensive analysis. Madrid is also a relevant study case as there is a wide set of open data sources which allow an interesting look at the interaction between different parameters. These include cadastral data with graphic and alphanumerical information, COVID-19 incidence data, mobility data from cell phones, and revenue data.

16.3.2 Research Design

This article is quantitative research that considers the geographical configuration of the Madrid region and the subjective input from the authors, who have worked and lived in the region for most of their life and have experienced there the COVID-19 crisis. The use of open data with high spatial and temporal resolution allows the obtention of detailed results and the replicability by other authors. Since the data spatial and chronological granularity is heterogeneous, the analysis considers these differences to reach conclusions. The research has followed the following sequence, with the aim to answer the following questions:

(A) Data preparation
(B) Analysis at the scale of the 246 census districts

   a. Basic morphological and demographic analysis
      i. Are population and housing stock moving the same way?
      ii. To which extent these changes are related to urban density?
      iii. Which are the morphological conditions of the areas that have witnessed more robust growth?
      iv. To which extent has there been a change in these dynamics before and after lockdown?
   b. Specific age group analysis
      i. Has population location evolved over time for different age groups?
      ii. Has there been a change in the distribution of age groups according to housing typology?

(C) Analysis at the 4.147 census tracts and their groups

   a. Is there any indication of links between urban density and disease dynamics?
   b. Is there any link with mobility indicators?
   c. Are there any density indicators that show a higher correlation with disease progression?
   d. Are there lessons from the evolution of the disease dynamics over time in relation to density?

(D) Conclusions

Further research will refine this approach to the problem as more detailed data is available, so its conclusions are provisional. Although there are data about the behavior of these indicators during the lockdown, its singular conditions have made the authors think that the recovery process was more interesting.

16.3.3 Data Preparation

We organized the research according to the following set of criteria:

1. Geographical study areas preparation (Fig. 16.1): All the building footprints defined in the state cadaster are subject to a double buffer process, to provide a homogeneous area measure for the floor-area ratio calculation:

   a. First, they are subject to a 50 m outward buffer. This 50 m dimension allows to differentiate urban tissues separated by large avenues and motorways, rail corridors, or linear parks, which can we assume to be urban interaction limits by breaking the domestic scale. We then dissolved the resulting polygons, as to provide a continuous buffer of the built footprint, regardless of the use of the building. Although in some cases, a minute analysis of the data shows uses classification issues due to the difference in criteria between the tax orientation of the source and the urban analysis use, overall, we consider it an accurate description of the current situation on the field.

b. Then, that overall buffer is subject to an inward buffer, also measuring 50 m. This provides a footprint that allows a density measurement which is consistent between zones, as more usual divisions as census tracts or health zones do not differentiate built-up areas from more open spaces. This way to measure density is intended to consider the potential interaction intensity between residents.

The resulting shape is then subject to two geometric operations:

i. Census district scale:

1. Results are intersected with the "distritos censales", as provided in Instituto Nacional de Estadística (2022d), providing a set of 246 polygons which, considering the geometric process, can have "islands" and "holes".
2. Morphological indicators regarding density and geometric configuration are related, according to the personal knowledge of the area by the authors, to the urban dynamics in the region. Table 16.1 shows the indicators used to generate each map. In demographic terms, children under 5 have been selected as the search for a better environment to raise them could be a driver to move to a different home after lockdown; the 65–69 age group corresponds to those just retired, who could also choose to move to a less dense place; and the over 69 group seemed interesting as they would seem to tend to stay in their homes.
3. On each map a table compares the results of the indicators for the affected set of census districts and compares those with the ones corresponding to the whole region. The two indicators to the right correspond to a geometric shape coefficient (geom), which is the result of dividing the area of the homogeneous area intersected with the census district by the square of its perimeter, to ensure a non-dimensional coefficient. For instance, a 2×2 square would have a coefficient of $4/8^2$, while a 4×1 rectangle, with the same area, would have a $4/10^2$ coefficient, hence the more compact the shape, the higher the coefficient. The second one is a floor-area ratio considering the sum of the built areas of any use according to the cadaster.

ii. Census tract scale:

1. Results are intersected with the "secciones censales" (census tracts) defined by the National Statistics Institute (INE). This step in this order is relevant, as even though these tracts are the building blocks for other zones as those related to health and mobility, the publicly disseminated shapefiles for the latter have been subject to a geometric generalization that would produce artifacts if geometrically overlapped as they are. The results are 4.417 polygons, one for each census tract, albeit with a morphologically defined boundary based on building footprints.

Table 16.1 Preparatory maps at the census district scale (*Source* authors, 2022)

	Rises between 2018 and 2022	Rises every year 2018–2022	Decreases 2018–2022	Decreases every year 2018–2022	Rises 2018–2020, decreases 2020–2022	Does not rise 2018–2020, rises 2020–2022
Nr single-family housing units	A1	B1	C1	D1	E1	F1
Nr multifamily housing units	A2	B2	C2	D2	E2	F2
Average surface of single-family housing units	A3	B3	C3	D3	E3	F3
Average surface of multifamily housing units	A4	B4	C4	D4	E4	F4
Average cadastral value of single-family housing units	A5	B5	C5	D5	E5	F5
Average cadastral value of multifamily housing units	A6	B6	C6	D6	E6	F6
Total population in the Padrón	A7	B7	C7	D7	E7	F7
Total population aged under five	A8	B8	C8	D8	E8	F8
Total population aged 65–69	A9	B9	C9	D9	E9	F9
Total population aged over 69	A10	B10	C10	D10	E10	F10

2. Then, each of the resulting polygons is assigned to the corresponding basic health zone and mobility analysis zone in independent text fields.
3. An additional field for each resulting polygon displays the area in m^2, as to provide density indicators.

2. Statistical data preparation:

   a. Data from the various sources is included in the database in different tables, in each case defining the corresponding original geographic coverage area.
   b. A set of joins allows to take account of that data in each analysis dimension (urban density, mobility, disease incidence rate…).

16.3.4 Open Data Used

Cadastral data. There are several methodologies to measure urban density, as in Berghauser Pont and Haupt (2009), which address the issue through specific measures. For this work, we chose to use official open built areas data. The Spanish Ministry for Budget produces and publishes open cadastral data for a set of 46 provinces, which includes Madrid, using different formats. There is an aggregate set of statistics that covers municipalities and "distritos censales" (census districts), summarizing for a set of land uses the number of properties and their basic features. The Madrid region has 179 municipalities, and 16 of them are subdivided into census districts, to a grand regional total of 246. Albeit this source has a low spatial granularity, it provides a temporal sequence that can be more informative than the detailed sources mentioned ahead, and it provides, at the graphical scale of this paper, a less detailed but clearer view of the whole region.

At a higher resolution, that of the individual parcel, there are two main sources. The national specification has a richer content but results in bulkier files, so we used the Inspire specification for buildings. The Ministry publishes Inspire-formatted data twice a year, and in this paper, we used the 2022 first dataset. This includes the building footprints that allow the previously explained homogeneous area delimitation. It also assigns a single land use to the complete set of buildings included in a lot, corresponding to the one which occupies the largest built area, and a figure for the number of dwellings in the lot and the built area. This number of dwellings is an approximation, as it really represents the number of invoices sent by the municipal tax office to individual real estate properties that have a residential use assigned. This means that when a single landowner rents several flats at a single address and is taxed for the whole, this appears as a single dwelling. As the proportion of rented dwellings in Spain and in Madrid is exceptionally low, and most of them are single dwelling properties, the differences between that dwelling number and other measurements, as that of the population of housing census, are generally small, so they are not taken into account. Besides, the currently available data census is from 2011, and as of March 2023, the National Statistics Institute has published the 2021 census data just for residents but not for buildings, so even if this last decade has seen scarce building activity, authors have chosen to use the cadastral data.

Population data. The Spanish National Statistics Institute produces two basic sets of population data. The first is the 10-year census, whose last published results are from 2011, and whose 2021 results are not yet available. The second one is the "Padrón Municipal de Habitantes", which is an administrative record of the residents in each municipality. When a resident in Spain is born or changes residence, concerned municipalities update the corresponding address along with basic data, avoiding double counts. As the inscription at a given address can provide access to public schools or services in specific locations, in large metropolitan areas there are cases of people living in an area but inscribed as residing in the municipality in which they work. For the purposes of this research, we considered that this is not significant.

The National Statistics Institute publishes this population data in its most detailed spatial resolution by "secciones censales" (census tracts), which correspond to around 1.000 residents on average, with 4.417 tracts for the whole region, which are subdivisions of the previously mentioned census districts. In densely populated areas, this covers an urban block, but in rural areas, they can cover the whole municipality. The published data informs about the total size of the population, its gender and age composition, place of birth, and education level. The Spanish National Statistics Institute publishes data at this resolution once a year, and municipalities as that of Madrid have started publishing monthly data; as this would only cover about a half of the population, we used homogeneous yearly data for the whole region.

The dataset that we analyzed (corresponding to the population on January 1, 2021) Instituto Nacional de Estadística (2022a) corresponds to 6.751.250 residents, a decrease of 28.640 (0,42%) from the January 1, 2020, figures (6.779.890). The Spanish National Institute for Statistics publishes specific data on residential variations that show how people move between addresses over a year. We have not evaluated this information as it is not available with enough granularity, and there has been also no data source to obtain detailed information about deaths resulting from COVID-19.

COVID-19 incidence data. The Health Department of the Madrid Regional Government has published data of the COVID-19 incidence rate, as measured per 100.000 residents, using the basic health zones' geographic boundaries (aggregates of census tracts) as the most detailed. The publications provide daily data for the lockdown period (March–June 2020), and since June 2020 twice a week. There are two open data formats: a 14-day mobile average, which better portrays local surges and the regional government used for local lockdowns, and an absolute incidence rate, which is a number that can only grow and not oscillate as the 14-day mobile average. The absolute incidence rate provides an approach to potential long-term impact, as unfortunately there is no data on the severity of the cases or the mortality at that scale.

The Madrid Regional Government publishes this data for the geometries of 286 Basic Health Zones.

Mobility data. In 2019, the Spanish National Statistics Institute started an experimental mobility study based on cell phone data, Instituto Nacional de Estadistica (2022b). As COVID-19 appeared, the National Statistics Instituto adapted that operation to provide data about the impact of the pandemic on mobility patterns. As in Spain there are over 55 million mobile lines for 47 million residents, this source seems representative. During the lockdown period, data showed that the overall mobility on a working day diminished to weekend levels. Following that period, and in a similar fashion to the COVID-19 incidence data, the publication frequency for this data was reduced by the National Statistics Institute. The information provided does not include the mobility mode, or speed, but focuses instead on the number of people that are during daytime and nighttime in each area, as well as the links between the areas in which people spend nights and days. For this study, we chose to pay attention to the quotient between the total population detected during daytime in an area and its resident population, which is the one staying at night.

The geometry of the areas of the Madrid Region on which this data is published is 295 polygons, which aggregate census tracts.

16.3.5 Data Processing and Visualization

The mentioned data has been processed through Microsoft 365 and the open-source QGIS for Windows software, using SQL expressions to filter and aggregate the original data to obtain the used indicators at each geographic scale. To get a global vision of the built density versus population density issues, a matrix of maps already described in the data preparation section has been created at the census district geographic detail, which given the final publishing format provides a clearer view. The maps in that matrix that have provided interesting results are figures in this article, along with those that, at other scales, provide further relevant results.

As there are two sets of maps, one at the census district detail scale and the other at the census tract detail scale, density figures are different, as the larger zones considered for census districts provide lower average densities; this is considered in the conclusions.

16.4 Results and Discussions

16.4.1 Census District Scale

This scale allows to consider overall dynamics for the building construction dynamics. As the analyzed period is quite short compared to the planning and permits pipeline, we chose to analyze building dynamics for multifamily and single-family housing units using the cadastral statistics between 2018 and 2022, covering the total figure as of December 31, of each year. The reason to obtain different figures for both typologies is related to the potential attraction that single-family homes could have after a lockdown in an overwhelmingly multifamily housing stock. As the total stock of housing units in the region during those 5 years rose by less than 1% overall, the test focused on whether the numbers rose or went down.

Overall, between 2018 and 2022, the number of housing units has grown in 219 of the 246 census districts; this growth, rendered in Fig. 16.2, has been limited in proportion and has favored multifamily housing units in absolute terms, with over 10.000 new units which are an 0,4% increase when compared to 2018, and single-family units in relative terms, as the over 4.000 additional units mean a 1,19%increase. This means that overall, the trend is to continue the relative increase in the presence of lower density urban tissues. A closer analysis shows that the largest increase in single-family units has been in areas where both typologies grow. Areas in group (a) in Fig. 16.2 are in peripheral locations which are less connected to the main roads, which could explain why only single-family units have grown; they are the less populated but have experienced the highest percentual population growth. In group (b), in which multifamily units have grown but not single-family ones, we find the densest urban tissues in the region; these have the most compact urban shape as the geom coefficient shows, and the highest floor-area ratio. In group (c), which is the scene for a growth in both typologies, are peripheral areas better connected to the main roads. This (c) group has a looser geom coefficient, but higher floor-area ratio than group (a), so are becoming more complex and gaining population faster than the denser tissues of group (b).

When analyzing population growth considering the 2020 (lockdown) threshold, most districts, and clearly those in more central locations in the metropolitan system, have gained population in the 2018–2020 period to later loose residents until 2022 (Fig. 16.3). The eight districts that had no growth prior to the lockdown are in extremely peripheral areas, and their total population is minute. The geom coefficient of these eight districts is quite like that of the opposite group, but with lesser FAR, as these are small rural settlements with compact urban shapes but limited building height.

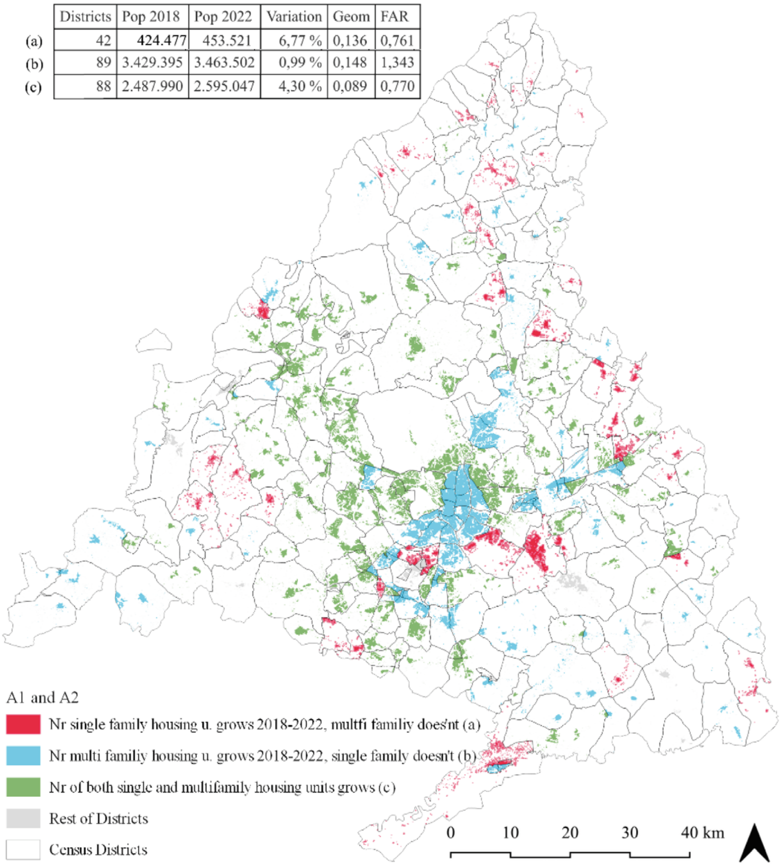
The specific 0–4 years old group shows a growth in peripheral areas, as it also happens in the case of the decrease (Fig. 16.4). The numbers show that the changes after 2020 have had a limited impact on the pre-lockdown dynamics. Areas losing toddlers after the lockdown that had previous growth in their number are slightly more compact but have smaller FAR than the opposite group.

Figure 16.5 shows that the districts that following the lockdown have gained retired residents are scattered around the region, but especially concentrated around the urban core, even though many of those are quite dense areas. Anyway, population gains have been quite reduced.

When it comes to the oldest groups of age, population losses are in the central city (Fig. 16.6). Further data would help to differentiate losses resulting from COVID-related deaths from other sources.

Overall, the analysis by age groups shows limited insight on any influence of the pandemic on the residential location. The fact that Spain and the Madrid region have

	Districts	Pop 2018	Pop 2022	Variation	Geom	FAR
(a)	42	424.477	453.521	6,77 %	0,136	0,761
(b)	89	3.429.395	3.463.502	0,99 %	0,148	1,343
(c)	88	2.487.990	2.595.047	4,30 %	0,089	0,770



	Single family housing units		Multifamily housing units		Overall 2018-2022 growth	
	2018	2022	2018	2022	Single family	Multifamily
(a)	39.152	39.834	136.737	136.394	682	-343
(b)	89.648	88.788	1.440.360	1.446.170	-860	5.810
(c)	210.323	214.893	803.340	808.711	4.570	5.371
Rest of districts	19.892	19.779	81.943	80.969	-113	-974
Grand total	**359.015**	**363.294**	**2.462.380**	**2.472.244**	**4.279**	**9.864**

Fig. 16.2 Composite map of A1 and A2 census district maps. Variation in the number of multifamily and single-family housing units by census district between 2018 and 2022 and summary table (*Source* authors, 2022)

a high rate of home ownership, which is more rigid in its changes than home renting, is relevant here. What this data does show is the fact that the low-density urban forms keep gaining residents at a faster pace than denser areas.

	Districts	Pop 2018	Pop 2022	Variation	Geom	FAR
E7	56	4.095.009	4.131.477	0,89 %	0,107	1,415
F7	8	5.234	5.527	1,37 %	0,122	0,309
Regional	246	6.578.079	6.750.336	2,62 %	0,108	0,959

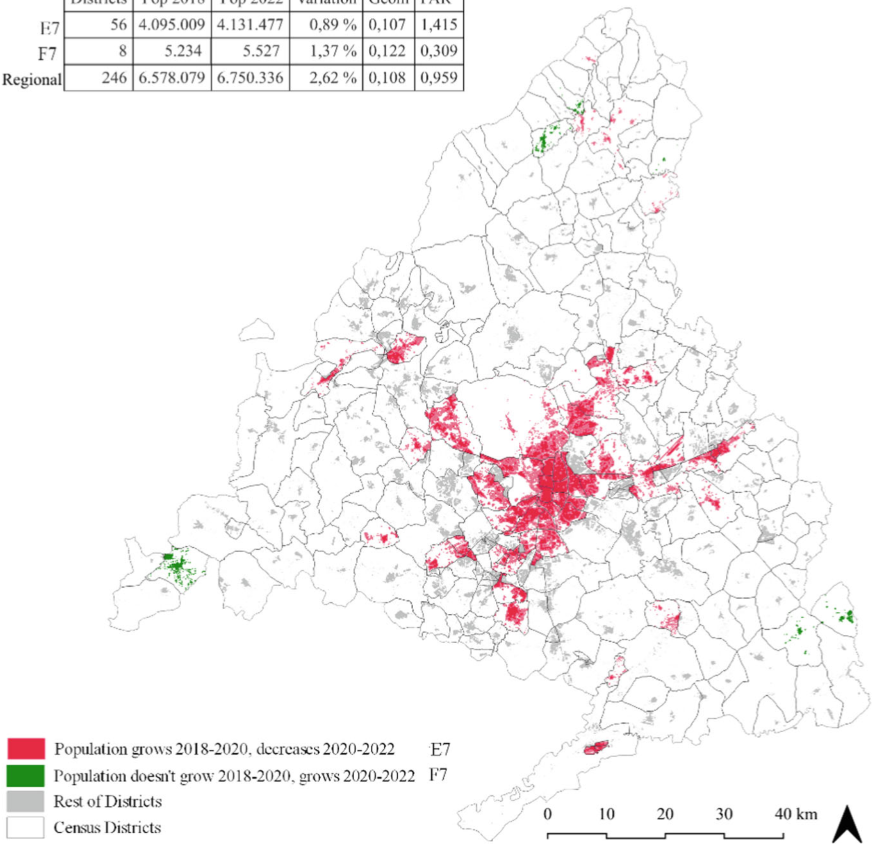


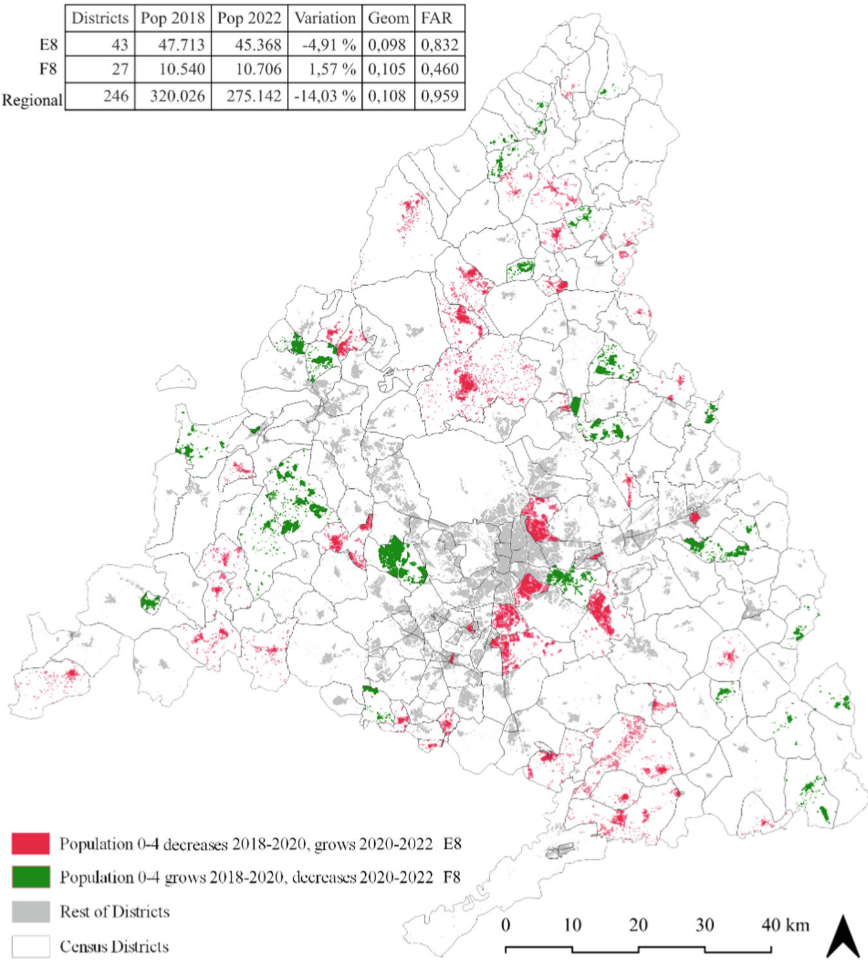
Fig. 16.3 Composite map of E7 and F7 census district maps. Variation in population by census district, considering the 2020 (lockdown) threshold (*Source* authors, 2022)

16.4.2 Census Tract Scale

16.4.2.1 Built Density

In terms of built density, displayed as a floor-area ratio that considers the homogeneous area definition prior described, the central city of Madrid, along with a set of suburbs in the nearest areas, have the highest values in the region. Most of central Madrid is over three m^2/m^2 as measured on homogeneous areas at the census tract level. Sixty-nine percent of the built-up area is on lots in which homes are the main use, 10% is on those on which industrial use is the main one, and 4% goes to retail and to offices.

The average dwelling density is of 45 dwellings per hectare, and there is a step gradient in which the densest areas are in the central city. Only 0,92% of the dwellings



	Districts	Pop 2018	Pop 2022	Variation	Geom	FAR
E8	43	47.713	45.368	-4,91 %	0,098	0,832
F8	27	10.540	10.706	1,57 %	0,105	0,460
Regional	246	320.026	275.142	-14,03 %	0,108	0,959

Fig. 16.4 Composite map of E8 and F8 census district maps. Variation in population aged 0–4 by census district, considering the 2020 (lockdown) threshold. Total regional numbers for population considered here just for the age group (*Source* authors, 2022)

recorded in 2022 were built after 2019, and the proportion of both overall built-up area and residential built-up area built after 2019 was close to 1,4%, which means there was an acceleration of growth, as only 3,57% of the recorded housing units in 2022 were built after that year.

The average built-up area per dwelling was 148 m^2, with a strong correlation at the regional scale between that parameter and household disposable income. The areas with the highest average built-up area per dwelling are usually in the richer districts of the inner city and in peripheral areas.

	Districts	Pop 2018	Pop 2022	Variation	Geom	FAR
E9	10	921	995	8,03 %	0,188	0,462
F9	48	77.206	77.823	0,80 %	0,111	1,127
Regional	246	320.026	275.142	-14,03 %	0,108	0,959

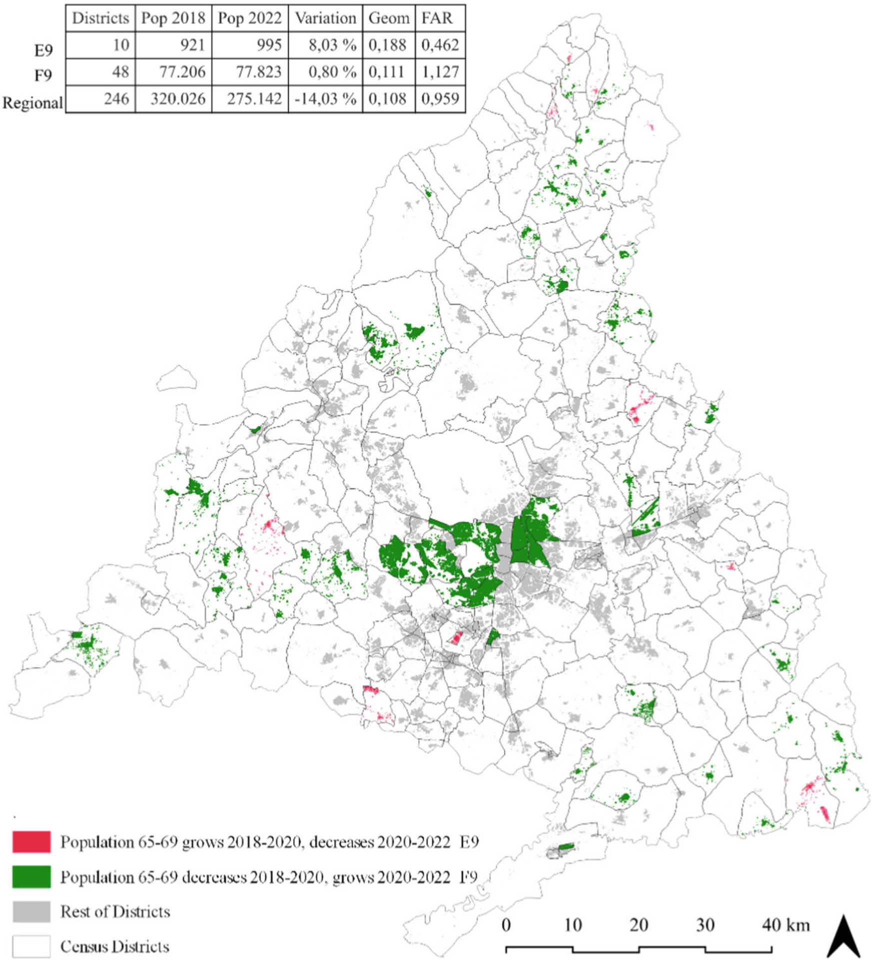


Fig. 16.5 Composite map of E9 and F9 census district maps. Variation in population aged 65–69 by census district, considering the 2020 (lockdown) threshold. Total regional numbers for population are for the age group (*Source* authors, 2022)

16.4.2.2 Population Density

The average population density of the defined areas as of January 1, 2022, was 105 persons/hectare, and there is a step gradient in which the densest areas are in the central city (Fig. 16.7). This is closely correlated to the average dwelling density.

	Districts	Pop 2018	Pop 2022	Variation	Geom	FAR
E10	34	342.364	338.897	-1,01 %	0,136	1,682
F10	10	1.642	1.643	0,06 %	0,211	0,416
Regional	246	320.026	275.142	-14,03 %	0,108	0,959

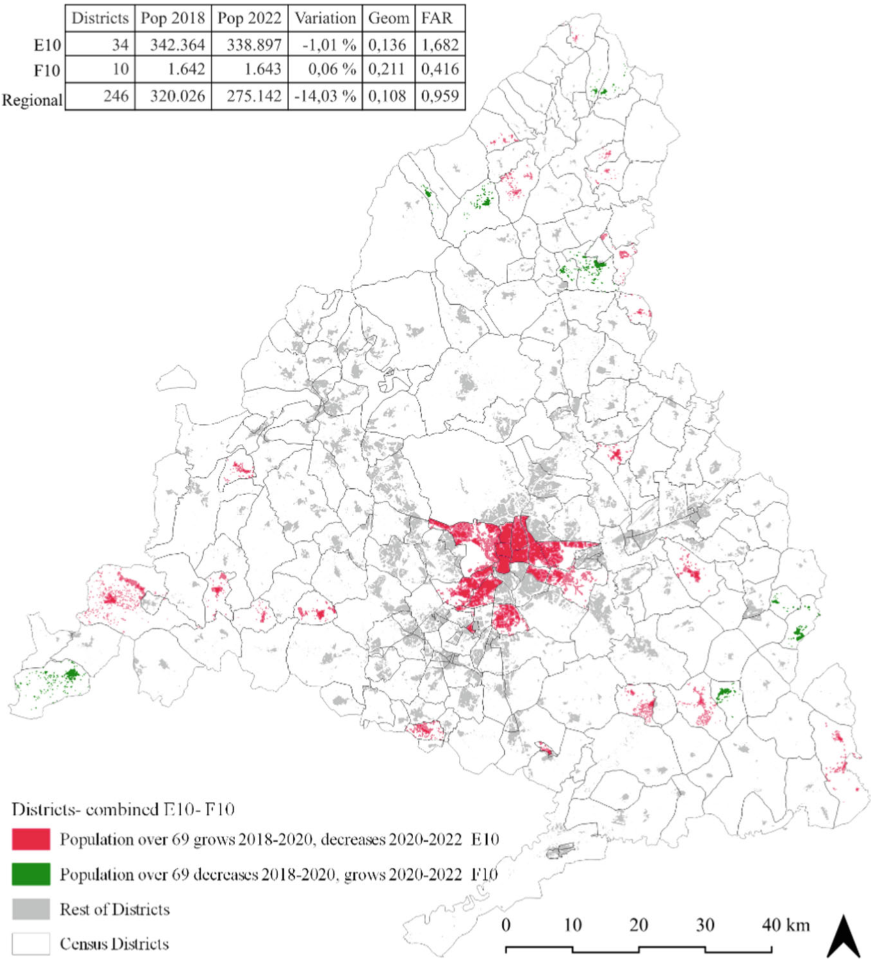


Fig. 16.6 Composite map of the E10–F10 census district maps. Variation in population aged over 69 by census district, considering the 2020 (lockdown) threshold. Total regional numbers for population are for the age group (*Source* authors, 2022)

16.4.2.3 COVID-19 Incidence

The COVID-19 incidence has evolved over time by a set of "waves" in which 14-day averages rose sharply to later decrease, getting at the end of the period to as high a 19.317 per 100.000 (Fig. 16.8). From March 2020 to August 2022, the estimated death toll for the Madrid Region has been of 19.112, with 1,91 million recognized cases. Over 5,7 million residents in the region received the double shot, and over 3,5 received a third dose.

In a first visual analysis, the higher overall ratios as of November 30, 2021, are in the densest central locations of the region (Fig. 16.8), but a quantitative analysis

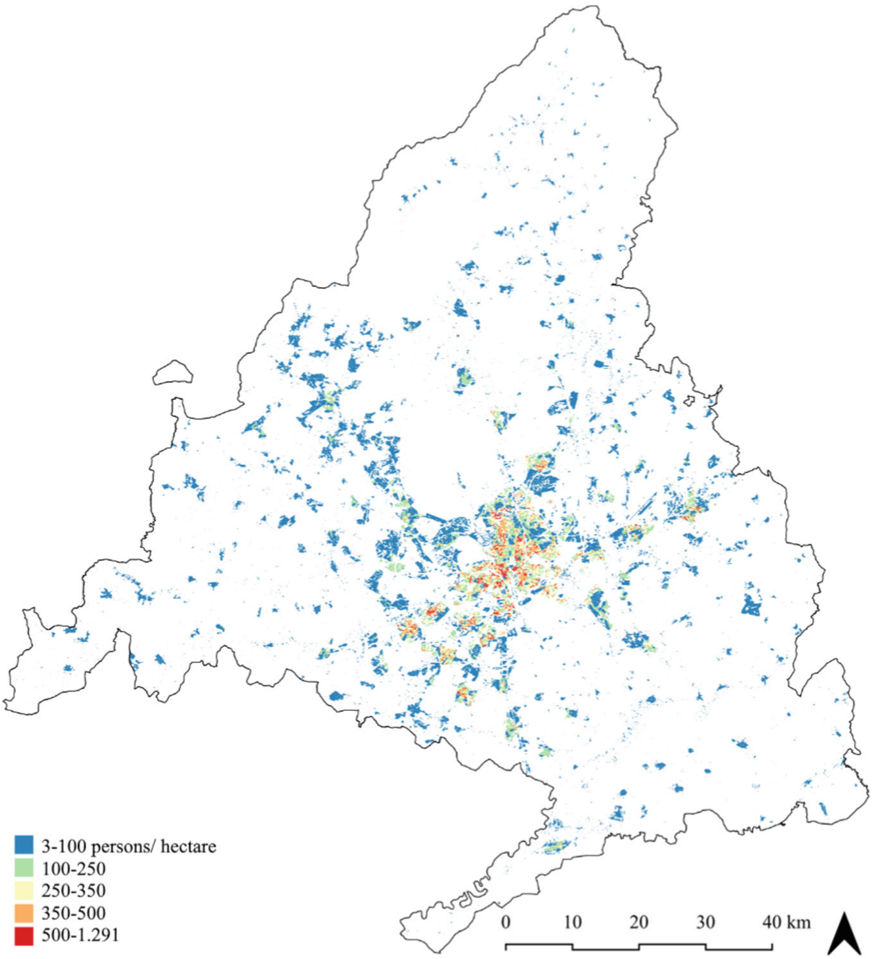


Fig. 16.7 Population density as of January 1, 2022, in persons per hectare (*Source* authors, 2022)

shows differences. When considering the built densities of each census tract and the cumulative incidence of the corresponding basic health zone, the correlation is weak, as R2 is just 0,0366. A more detailed data on incidence, by census tract, could provide more insight, as would data about the severity of infections at that spatial resolution. When we evaluate the correlation against built-up surfaces (Fig. 16.9) the R2 value decreases. Parallel research published in Barros-Guerton and Ezquiaga-Dominguez (2023) shows a coincidence of these results with those for the central city of Madrid, although in certain moments of the second wave there seemed to be a strong correlation between home size and disease (Fig. 16.10).

Figure 16.11 shows the Pearson correlations between different indicators; in each case CIR is the highest published data for each area, built-up areas and numbers of

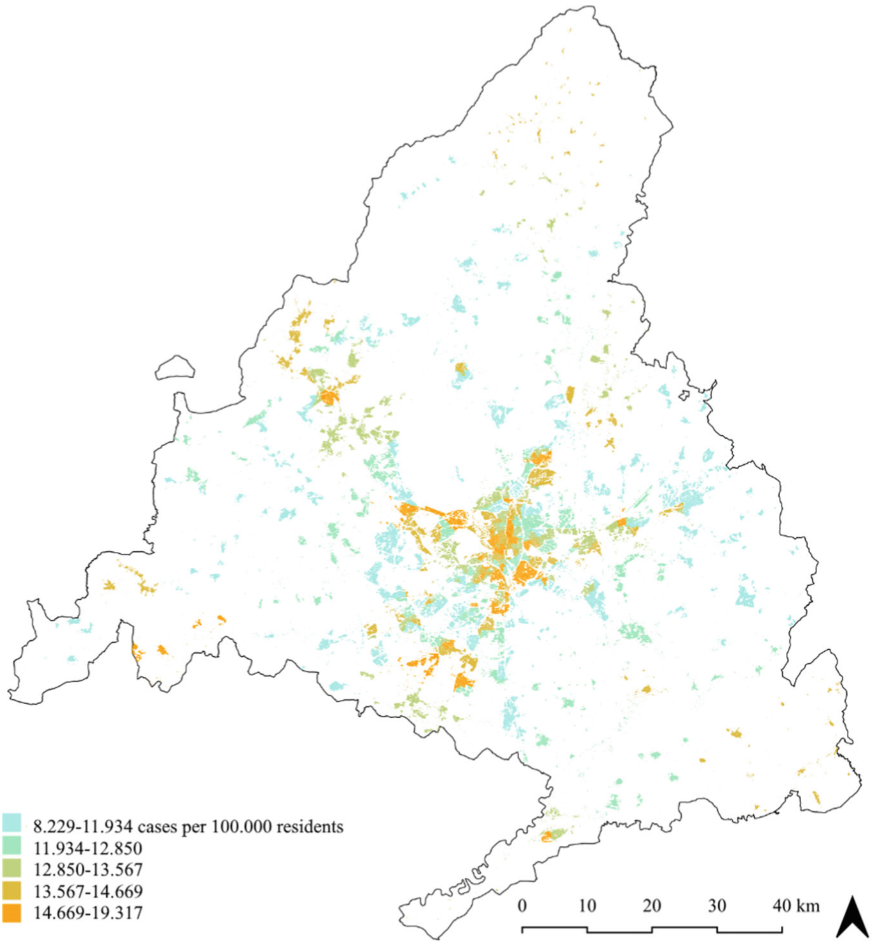


Fig. 16.8 Overall cumulative incidence rate for COVID-19 by basic health zone, as of November 30, 2021, according to the Regional Government data, in cases per 100.000 residents (*Source* authors, 2022)

dwellings are the 2022 data; the change in built areas between 2020 and 2022 has been quite minute, as it has become evident in previous sections, so the figures are considered constant, and there are specific indicators for change. Adopting a more dynamic analysis from June 2020 to March 2022, it becomes clear that the stronger Pearson correlations on a regional scale have happened after the 2020 summer, with a +0,542 for persons/hectare versus CIR, meaning that the more crowded the home, the higher the chance of getting infected, and a −0,610 for m^2/dwelling versus CIR, meaning that the higher the home surface, the lesser the chance of infection. The third highest correlation, also around that time, is for the dwellings per hectare correlation, at 0,482. It is strange that the correlation between persons per dwelling and CIR is

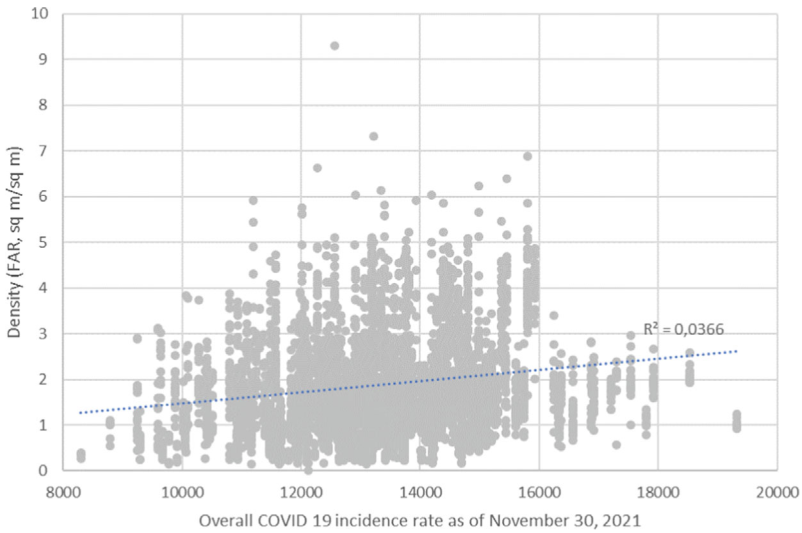


Fig. 16.9 Overall Cumulative Incidence Rate for COVID-19 by basic health zone, as of November 30, 2021, according to the Regional Government data, in cases per 100.000 residents, in correlation with built-up density (FAR in m^2/m^2) (*Source* authors, 2022)

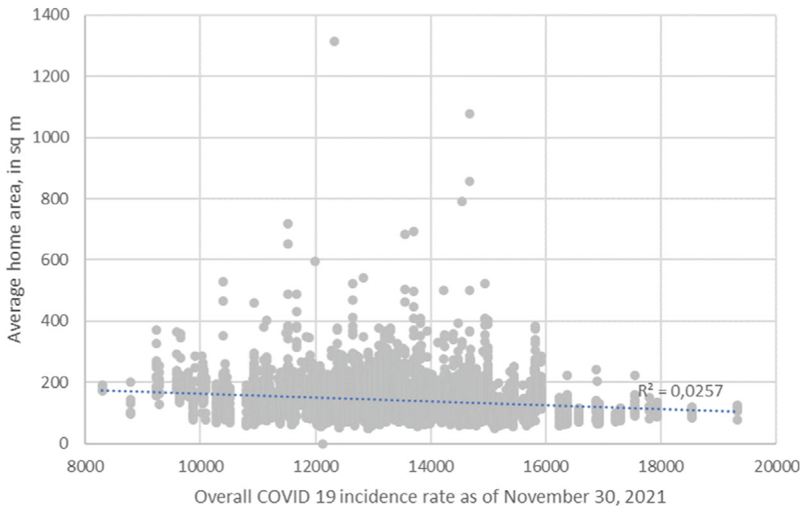


Fig. 16.10 Overall Cumulative Incidence Rate for COVID-19 by basic health zone, as of November 30, 2021, according to the Regional Government data, in cases per 100.000 residents, in correlation with average home built-up area in m^2 (*Source* authors, 2022)

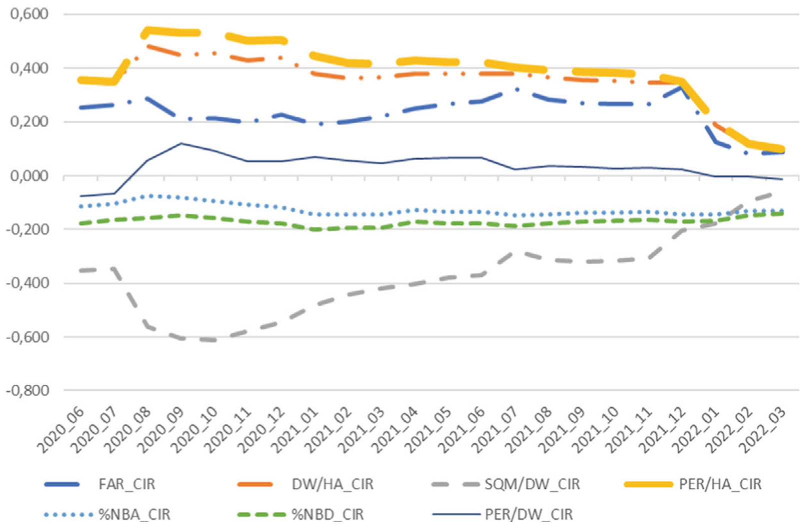


Fig. 16.11 Evolution of the Pearson correlation coefficient between the highest COVID-19 Cumulative Incidence Rate (CIR) for each month between June 2020 and March 2022 in the Madrid Region. FAR: floor-area ratio, DW/HA: dwellings per hectares, SQM/DW: square meters per dwelling, PER/HA: persons per hectare, %NBA: % of built-up surface erected after 2019, %NBD: % of dwellings erected after 2019, PER/DW: persons per dwelling (*Source* authors, 2022)

quite low, but this can be since in some areas there are substantial number of vacant dwellings. A gradual flattening of those curves is subject to a clear change from January 2022, coinciding with a methodology change for case accounting.

16.4.2.4 Mobility Data

We approached mobility by counting, among the 150 days with published cell phone data between June 2020 and November 2021, those in which the number of daytime persons exceeded that of nighttime residents (Fig. 16.12). In 3.559 areas (80,5% of the total areas, with 81,91% of the population) no single day complied with that rule, which means they overall sent more people to work, study or receive services in other areas than they received. On the remaining 858 areas the highest numbers of days correspond overwhelmingly to the central city and, to a lesser degree, to economically relevant locations (Barajas airport), in high-income low-density residential areas (La Moraleja). This also applied to sparsely populated municipalities in the northern tip of the region which may have been a temporary shelter for people which the Padron Municipal de Habitantes recorded as living in other areas, and its relevance has increased by the low recorded density prior to the COVID-19.

To get an idea on how this has evolved over time we applied a simple test. As the June 2020 to November 2021 period covers 18 months, have the areas experienced more days complying with the defined condition during the first 9 months or during

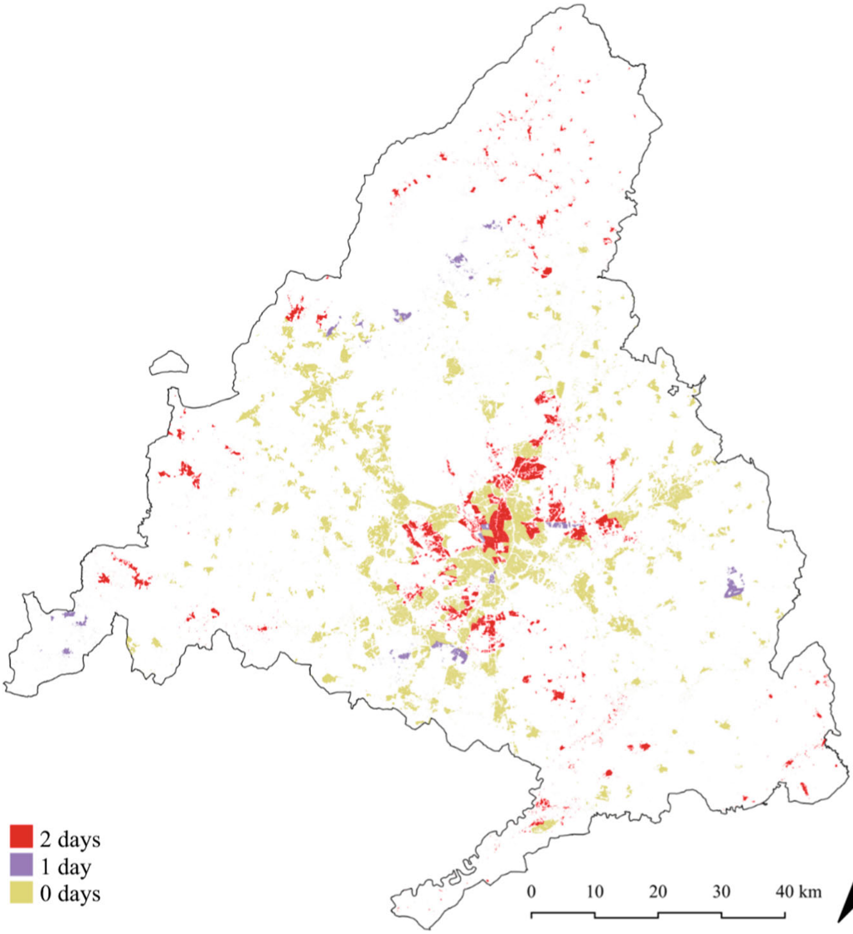


Fig. 16.12 Number of days with data in the June 2020–November 2021 period in which the number of persons present during daytime in the area was larger than that of residents at nighttime. 0 = no recorded days with such condition. 1: more than one recorded day, and most of the days were in the first 9 months of the interval. 2: more than one recorded day, and most of the days were in the second half of the interval (*Source* authors, 2022)

the later? Among the sixty-three mobility areas which overall complied with the condition, only in fifty-three there were more days of compliance during the second half of the period. These fifty-three areas follow a similar pattern of use and density to the one described above. Meanwhile, the areas in which the number of days with more visitors than residents fell correspond to low-density areas in which secondary dwellings (i.e., holiday houses or flats) were used after lockdown, to later return to permanent housing units in denser areas.

So, in terms of mobility, the lockdown, and the perception of low quality of life in smaller multifamily multistorey units compared to that in low-density areas

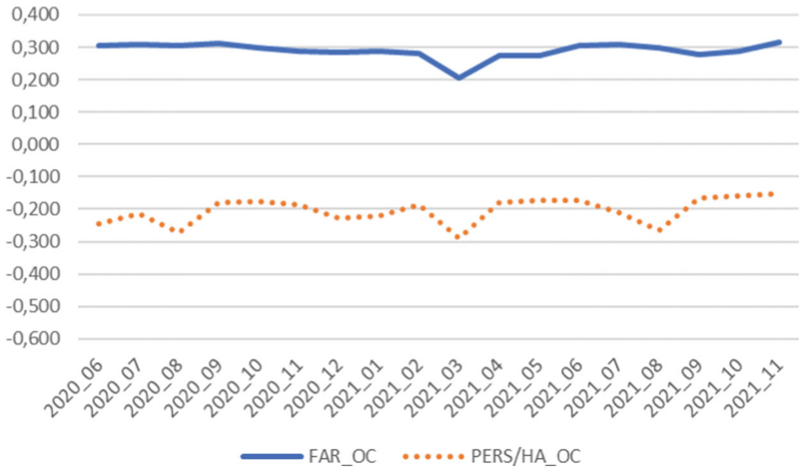


Fig. 16.13 Evolution of the Pearson correlation coefficient between the highest monthly ratio for the daytime population versus nighttime population and Floor-Area Ratio (FAR) and density in persons per hectare (PERS/HA), for Wednesdays (*Source* authors, 2022)

created a certain displacement of residents, which later tended to return to their usual dwellings, which have better access to services.

A further refinement along the 150 days of that period is to differentiate between Wednesdays and Sundays, the two days of the week for which there are data. When just taking into account to which extent the floor-area ratio, as a measure of density, is related to daytime arrival of visitors, the direct correlation for Wednesdays (Fig. 16.13) is direct but low (0,3) and lesser for Sundays (Fig. 16.14); when considering human density in persons per hectare the Wednesday correlation is negative but weak, but on Sundays it is higher, around 0,45, and negative, so the higher the human density of residents, the lower the chance to have people coming from other areas on Sunday. More detailed data from non-pandemic moments could confirm whether this was a result of the psychological pressure of lockdown, or it is a social constant in Spain, but it seems consistent with the perception of the authors that the lockdown experience played a relevant role.

16.5 Conclusions

The complexity of the COVID-19 pandemic and its long duration has made it difficult to identify single factors of correlation with the disease, as it has had consequences on urban tissues that were already under complex situations in Spain due to an economic crisis that has lasted for more than a decade. Overall, the results show that urban density alone is not necessarily a driver of the spread of the disease, as initially claimed by the mass media as in Rosenthal (2020) and Gracia (2020).

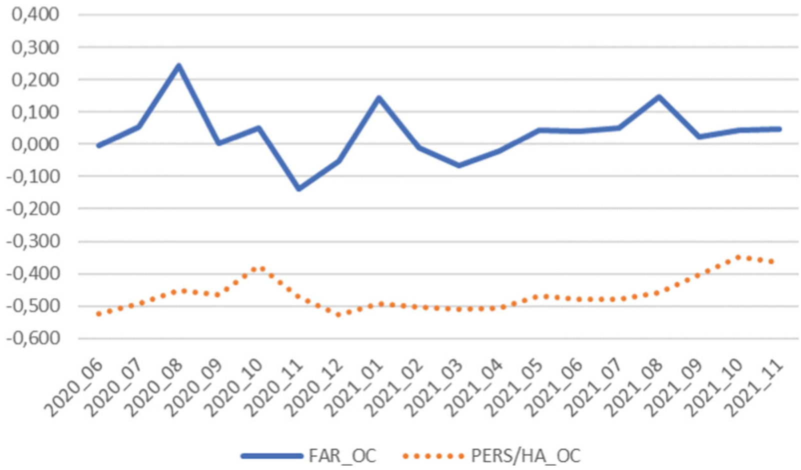


Fig. 16.14 Evolution of the Pearson correlation coefficient between the highest monthly ratio for the daytime population versus nighttime population and Floor-Area Ratio (FAR) and density in persons per hectare (PERS/HA), for Sundays (*Source* authors, 2022)

Data shows some signs that the main effects of COVID in terms of urban dynamics, besides the obvious decrease in street-level economic activity that has crippled many businesses, have been some increases in daytime population in low-density peripheral areas which can be related to a temporary use as a main residence of what usually was a secondary home, and this has decreased over time. According to mobility data, the areas that have a greater population during daytime than at night are still the central areas of the core city and some peripheral locations that are related to high economic activity; a substantial difference in the correlation between human density and the degree of attraction on Sundays, in the negative sense, seems coherent with a stringently felt lockdown. On the other hand, the changes in the overall population over the 2020 year contrast sharply with those corresponding to the 0–4 years age group; further work could establish whether a trend to move to lower density areas when having children is intensifying, or this was a response to the trauma caused by lockdown in small apartments which often lack good access to sun and open views in the densest area of Madrid, or other factors are at stake.

The complexity of the analyzed data and the absence of disease data at the census tract scale can mask interesting results; there is a strong correlation between population density and home size versus cumulative incidence rate in the first wave after the lockdown. This would be consistent with other historical pandemics, in which home overcrowding played a role in disease transmission, so it seems reasonable to think about the housing standards in planning documents and the adequate provision of decent housing as a positive measure against future epidemics. Even if that correlation has decreased, the fact that it was high during a second wave in which personal movement was unimpeded, could point to the fact that less densely occupied housing units would have resulted in lower incidence.

The existing data is detailed, but it shows its limits when subject to scrutiny, as the use of sources with different aims can mask some outcomes. For instance, the cadastral data used does not provide information on whether a building is in use. A Regional Digital Twin would need further refinements of those tools, taking into acount the complexity of interactions and coertions as stated in Guerton and Dominguez(2022).

As referred in Barros-Guerton and Ezquiaga-Dominguez (2023), mobility patterns in the inner city are changing, and there is a chance that telecommuting, enabled by the internet, could be a substantial part of that change.

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