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Urban Heat Islands and Inequalities: Evidence from French Cities[1]

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ABSTRACT

During heatwaves, urban heat islands (UHI) affect cities neighborhoods heterogeneously due to differences in urban form, building quality, vegetation, and human activity. Some populations are particularly vulnerable, such as older adults and young children or low-income households, who have fewer options facing UHI. In this paper, for the first time, we measure UHI exposure among households depending on their income in the major French cities. We build and match finely localized data on temperature, vegetation, residential building density, height and period of construction, and households socioeconomic characteristics across nine of the largest French cities. We find that the relationship between UHI exposure and income depends on their pre-existing spatial sorting. In cities like Paris, the French capital, where both affluent and low-income households reside close to the city center, UHI exposure by income follows a U-shaped curve. In contrast, in cities where affluent households live in rich suburbs, like Lyon, France's second largest city, UHI exposure decreases with income. We also find that vulnerable households, defined by both age and income criteria, are slightly more exposed but far less able to renovate their dwellings or leave cities during heatwaves.

Keywords: Climate Change; Urban Heat Islands; Urban Areas; Spatial Inequalities

JEL classification: Q54; R11; R14

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NON-TECHNICAL SUMMARY

As the effects of global warming intensify, cities, where nearly 70% of humanity will live by 2050, face a major challenge. Climate change leads to an increase in the frequency, intensity and duration of heatwaves, even in temperate climate countries. Heatwaves once considered exceptional, such as the 2003 event in France, could become the new norm by the end of the century and occur during a larger part of summer. The urban environment exacerbates the effects of heatwaves, creating urban heat islands (UHI). Urban concentration leads to higher temperatures, especially at night because poor-quality building materials, roads, and infrastructure absorb and retain heat. UHI are also amplified by the lack of green spaces and vegetation and by the heat generated by human activities (engines, air conditioning).

Extreme temperatures can be the direct cause of death by provoking heat stroke, hyperthermia, and dehydration. Some populations are particularly vulnerable, such as older adults and young children, but also low-income people, because they present a more fragile state of health than the population as a whole. In addition, low-income populations cannot afford to leave the city during heatwaves to go to rentals or second homes, as wealthier households do. Their prime coping strategy consists in staying at their homes with poor insulation, where they lack agency over thermal situation, in particular with less means to cool their dwellings with air conditioning.

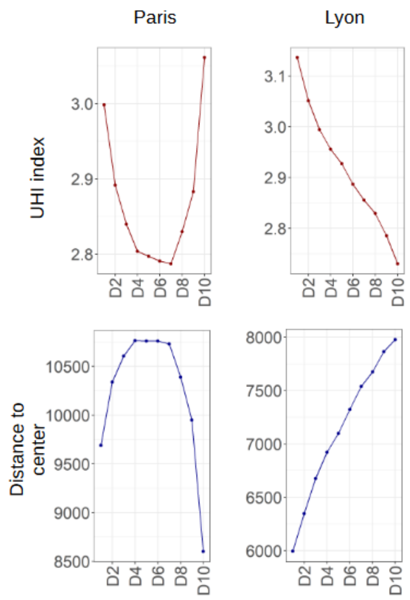
This paper presents the first analysis of climate inequality with respect to UHI in France. We measure UHI exposure among households depending on their income in the major French cities. To do so, we produce unique highly granular databases by compiling and matching finely localized data on temperature, vegetation, residential building density, height and period of construction, and households socioeconomic characteristics across nine of the largest French cities.

We find that the relationship between UHI exposure and income in a city depends on households spatial sorting by income. In Paris, Bordeaux, Lille, and Nantes, high- and low-income households live closer to the city center than median-income households, and UHI exposure follows a U-shape curve, particularly pronounced in Paris. In Lyon, Montpellier, Marseille, Nice, and Strasbourg, affluent households live in rich suburbs, and UHI exposure decreases with income. We also show that in all cities, except Paris for density, wealthier households live on average in greener, less dense neighborhoods with lower buildings. In cities where wealthy households live close to the city center, they also typically reside in older neighborhoods. In contrast, in cities where they live farther from the city center, they tend to reside in newer neighborhoods.

To guide public policy interventions, we identify the primary sources of unequal exposure to UHI by income across cities and we quantify their contributions to the unequal exposure to UHI by income deciles. First, building density, then vegetation and building height contribute to a decreasing relationship of UHI exposure with income in all cities, except Paris for density. The period of residential building construction in neighborhoods partly explains the varied U-shaped in the first group of cities and decreasing curves of UHI exposure by income in the second one. Lastly, as poorer households already live in denser, less green, and taller neighborhoods on average, we warn policymakers of the potential regressive impacts that mitigating policies may have.

Finally, we focus on vulnerable households, defined on age and income criteria and find that, in all cities, they are slightly more exposed to UHI than non-vulnerable ones. This difference in UHI exposure is mainly driven by the income criterion. Besides, we show that vulnerable households are less likely to improve their home insulation as they are much less likely to own their homes, to escape the city during heatwaves as they rarely possess secondary dwellings, or to cool their dwellings as the possession of an air conditioning system increases with income. We discuss the practical feasibility of exposed households limiting their use of air conditioning, which exacerbates heat stress outdoors.

Figure 1. Urban heat island index and distance to city center by income across cities



Note: In Paris, UHI index has a U-shaped relationship with income; distance to city center is bell-shaped with respect to income. In Lyon, UHI index and distance to city center are respectively increasing and decreasing with income. Data sources: Copernicus Climate Change Service, Fideli.

Îlots de chaleur urbains et inégalités : L'expérience des villes françaises

RÉSUMÉ

Pendant les vagues de chaleur, les îlots de chaleur urbains (ICU) affectent les quartiers des villes de manière hétérogène en raison des différences dans la forme urbaine, la qualité des bâtiments, la végétation et l'activité humaine. Certaines populations sont particulièrement vulnérables, comme les personnes âgées, les jeunes enfants ou les ménages à faibles revenus, qui ont moins d'options face aux ICU. Dans cet article, nous mesurons pour la première fois l'exposition aux ICU des ménages en fonction de leur revenu dans les principales villes françaises. Nous construisons et comparons des données finement localisées sur la température, la végétation, la densité des bâtiments résidentiels, la hauteur et la période de construction, ainsi que les caractéristiques socio-économiques des ménages dans neuf des plus grandes villes françaises. Nous constatons que la relation entre l'exposition aux ICU et le revenu dépend de la répartition spatiale préexistante. Dans des villes comme Paris, la capitale française, où les ménages aisés et à faibles revenus résident à proximité du centre-ville, l'exposition aux ICU en fonction du revenu suit une courbe en forme de U. En revanche, dans les villes où les ménages aisés vivent dans de riches banlieues, comme Lyon, la deuxième ville de France, l'exposition aux ICU diminue avec le revenu. Nous constatons également que les ménages vulnérables, définis à la fois par des critères d'âge et de revenu, sont légèrement plus exposés mais beaucoup moins capables de rénover leur logement ou de quitter la ville pendant les vagues de chaleur.

Mots-clés : changement climatique ; îlots de chaleur urbains ; zones urbaines ; inégalités spatiales.

1 Introduction

As the effects of global warming intensify, cities, where nearly 70% of humanity will live by 2050 (United Nations and Social Affairs 2019), face a major challenge. Climate change leads to an increase in the frequency, intensity and duration of heatwaves (IPCC 2023), even in temperate climate countries and whatever the considered temperature scenario (Ouzeau et al. 2016). Heatwaves once considered exceptional, such as the 2003 event in France,[1] could become the new norm by the end of the century and occur during a larger part of summer. The urban environment exacerbates the effects of heatwaves, creating urban heat islands (UHI) (IPCC 2023). Urban concentration leads to higher temperatures, especially at night (Stone et al. 2010) because poor-quality building materials, roads, and infrastructure absorb and retain heat. UHI are also amplified by the lack of green spaces and vegetation (Peng et al. 2012, Upreti et al. 2017),[2] and by the heat generated by human activities (engines, air conditioning) (EPA 2023b). Worldwide, between 2003 and 2020, surface temperatures in cities were sometimes up to 10-15°C higher than in their rural surroundings (Zulian et al. 2022).[3]

Extreme temperatures can be the direct cause of death by provoking heat stroke, hyperthermia, and dehydration.[4] They also increase air pollution and respiratory diseases (ACPR 2024). Some populations are particularly vulnerable, such as older adults and young children, but also low-income people, because they present a more fragile state of health than the population as a whole (OECD 2017), or outdoor workers and homeless, because they spend a large amount of time outside (EPA 2023a). In addition to their more fragile health, low-income populations are particularly vulnerable (EPA 2023a) because they cannot afford to leave the city during heatwaves to go to rentals or second homes, as wealthier households do. Their prime coping strategy consists in staying at their homes with poor insulation (Fontès-Rousseau et al. 2022), where they lack agency over thermal situation (Berger et al. 2022), in particular with less means to cool their dwellings with air conditioning (Davis and Jarvis 2021).

This paper presents the first analysis of climate inequality with respect to UHI in France. We measure UHI exposure among households depending on their income in the major French cities.

To do so, we produce unique highly granular databases by compiling and matching finely localized data on temperature, vegetation, residential building and households so-

[1]In France, the 2003 event, which caused the death of 15,000 people (Inserm 2023), will correspond to a typical event at the end of the century, with much lower duration and intensity than the strongest waves that could occur over the last 30 years of the 21st century (Ouzeau et al. 2016).

[2]Han et al. 2024 estimate the significant impact of trees on mitigating urban heat. Hamel et al. 2021 provide a method to quantify and map the diverse benefits of natural infrastructure.

[3]For example, according to Institut Paris Region (Cordeau 2023), during the 2003 heatwave temperatures were up to 10°C higher at night between the heart of Paris and the outer suburbs.

[4]See Hajat and Kosatky 2010 for a review of heat-related mortality. On average, UHI-induced related mortality is associated with economic impacts of €192-€314 per adult urban inhabitant per year in Europe, comparable to air pollution and transit costs (Huang et al. 2023). UHI also limit functioning of key infrastructure, including transportation, water, sanitation and energy systems (IPCC 2023). See Hoffmann 2019 for an estimation of the benefits of adaptation to extreme climate events, in particular heat waves, focusing on nonmarket damages.

cioeconomic characteristics across nine of the largest French cities.[5] First, we utilize an exhaustive administrative database of French households and their principal residences. This database includes detailed information on household income, the age of household members, and the precise coordinates of each dwelling. We derive measures of residential building density, height and quality using information in the database on the surface area, maximum number of floors, and construction period of the buildings. Besides, we produce an UHI index on a 100-meter by 100-meter grids relying on outdoor two meters above ground temperature data coming from a climate model. We generate a vegetation index utilizing satellite data at the same 100-meter by 100-meter scale. We also calculate the distances from dwellings to both the city center and the nearest hospital. Ultimately, we create two databases, one at the household level and the other at the tile level. Both include household-related variables (such as income, age, tenure status, ownership of secondary dwellings, residential building height and period of construction, and distances to the city center and nearest hospital) and tile-related variables (UHI index, vegetation index, residential building density).

Conversely to the existing literature that predominantly conducts comparisons across geographical units, our household-based approach is particularly well-suited to studying climate inequality in terms of income. Using household-level income data instead of tile-level averages prevents income differences from smoothing out, as there is substantial household heterogeneity within tiles.

We find that the relationship between UHI exposure and income in a city depends on households spatial sorting by income. Brueckner et al. 1999 explain the existence of two types of cities - one where wealthy households live downtown, and the other where they live in the suburbs - depending on the relative (historical, social) amenity advantage of the center over the suburbs. In Paris, Bordeaux, Lille, and Nantes, high- and low-income households live closer to the city center than median-income households, and UHI exposure follows a U-shape curve, particularly pronounced in Paris. In Lyon, Montpellier, Marseille, Nice, and Strasbourg, affluent households live in rich suburbs, and UHI exposure decreases with income. We also analyze the relationship between vegetation, residential building density, height and period of construction, and income. Wealthier households live on average in greener, less dense neighborhoods with lower buildings in all cities, except Paris regarding density. In the French capital, wealthier households live in denser neighborhoods. In cities where wealthy households live close to the city center, they also typically reside in older neighborhoods. In contrast, in cities where they live farther from the city center, they tend to reside in newer neighborhoods.

In order to guide public policy interventions, we identify the primary sources of unequal exposure to UHI by income across cities. We conduct a straightforward econometric analysis where we regress the UHI index in each tile against vegetation, residential building density, height, and period of construction. We then quantify the contributions of these variables to the unequal exposure to UHI by income decile. First, residential

[5] Here and hereafter, the word *city* refers to urban areas (*"aires urbaines"*), which are similar to the metropolitan statistical areas (MSA) in the United States, while the word *city center* refers to the urban unit (*"unités urbaines"*), which is the central part of an urban area.

building density, then vegetation and residential building height contribute to a decreasing relationship of UHI exposure with income in all cities, except Paris. In the French capital, density contributes to a decreasing relationship of UHI exposure with income. Conversely, in cities where the wealthy live close to the city center, the fact that affluent households live on average in older neighborhoods contributes to the U-shaped curve of the UHI exposure with respect to income. In cities where the wealthy live farther from the center, the fact that they also live on average in newer neighborhoods, further contributes to the decreasing UHI exposure with respect to income. Lastly, as poorer households already live in denser, less green, and taller neighborhoods on average, we warn policymakers of the potential regressive impacts, both in terms of initial exposure and income, that mitigating policies may have.

Finally, we focus on vulnerable households. We propose a definition of vulnerable households based on age and income criteria; these are households where at least one member is over 65 or under 10, and whose income is below the poverty line, i.e. 60% of median income. We find that in all cities, vulnerable households are slightly more exposed to UHI than non-vulnerable ones. This difference in UHI exposure is mainly driven by the income criterion and is higher when considering income alone. We also analyze the strategies available to vulnerable households when facing and coping with the adverse effects of UHI. Vulnerable households are less likely to improve their home insulation as they are much less likely to own their homes. They are also less likely to escape the city during heatwaves as they rarely possess secondary dwellings. They also are less likely to be able to cool their dwellings as the possession of an air conditioning system increases with income. Lastly, we discuss the practical feasibility of exposed households limiting their use of air conditioning, which exacerbates heat stress outdoors.

If the relationship between income and several environmental risks has been described in France (see Fosse et al. 2022 for a review about air and soil pollution for example), this is not the case regarding UHI exposure and our paper fills this gap. The issue of climate inequality, which is identified at the worldwide scale (Castells-Quintana and McDermott 2023), is much more prevalent in the United States. People of color and those living below the poverty line are disproportionately exposed to UHI intensity in 169 of the largest American cities (Hsu et al. 2021) and in the vast majority of American counties (Benz and Burney 2021). In the United States, low-income individuals are 11% more likely than non-low income individuals to currently live in areas with the highest projected extreme temperature mortality impacts with 2°C of global warming (EPA 2021). In Canada, journalists have drawn maps and provided key statistics between temperature, income, and vegetation in seventeen major cities (Shiab and Bouchard 2022). In France, first rough maps - with neither statistics nor comments - of respectively temperature, income, and vegetation in four cities (Paris, Lyon, Marseille, Toulouse) have been drawn by journalists (Rossi and Rivière 2022). Chakraborty et al. 2019 study 25 cities around the world (including one French city, Paris), and find that in 18 of them, but not in Paris, poorer neighborhoods experience elevated heat exposure, an issue that occurs for both developed and developing cities alike.

The paper is organized as follows. In Section 2, we present stylized facts, our detailed data on temperature, vegetation, buildings, and socio-demographics within nine large

French cities, and key descriptive statistics. Section 3 discusses the relationship between UHI exposure and income across cities. It also analyzes the relationship between income and vegetation or residential buildings characteristics (density, height, period of construction) in the neighborhood of residence. Lastly, it quantifies the main contributors to the unequal exposure to UHI by income across cities. Section 4 compares UHI exposure and available options to cope with UHI for vulnerable versus non-vulnerable households. Section 5 concludes.

2 Context and data

We collect, produce and match finely localised data on temperature, vegetation, building density and quality, and socio-demographic characteristics of inhabitants within nine of the largest French cities.

2.1 Exposure to urban heat islands in France

In France, 80% of the population lives in cities (Costemalle 2020) and 14% of the population in areas where there will be more than 20 abnormally hot days in summer (Fontès-Rousseau et al. 2022). These hot spells are particularly damaging to the health of the most vulnerable, especially the elderly. The areas most exposed to abnormal heat are home to almost 1.2 million people living below the poverty line, sometimes in poorly insulated housing.

The Mapuce project models heat island effects in 42 major French cities and reveals inequalities between French cities (Gardes et al. 2020). The Paris conurbation is by far the most exposed to UHI, with many areas experiencing temperatures 4-6°C higher than in the Ile-de-France countryside, and peaks in the central districts of Paris between 2000 and 2009.[6] Indeed, results show that the larger the population of cities, the more they exacerbate heat retention and also that mountainous and semi-continental climates favor the intensity of UHIs, unlike immediate proximity to the coast (less than 10 km).

The UHI phenomenon is also highly correlated with absolute temperatures in all climate zones (Harmay and Choi 2023). In France, we find that the UHI effect is higher in cities located in the south.[7]

2.2 Constructing our datasets

We collect and produce finely localised data on temperature, vegetation, building quality, and socio-demographic characteristics of inhabitants within the largest French cities: Paris, Lyon, Marseille, Bordeaux, Nantes, Lille, Montpellier, Strasbourg, Nice (see Figure

[6] See also maps provided by Institut Paris Region, https://www.institutparisregion.fr/environnement/changement-climatique/chaleur-sur-la-ville/.

[7] We compare monthly mean absolute temperatures using data from weather stations (https://meteo.data.gouv.fr/datasets/donnees-climatologiques-de-base-mensuelles/) with the UHI index that we construct with our data (Section 2.2). We find a statistically significant linear coefficient correlation of 0.5.

13 in Appendix A.1 for the location of the nine cities in the map of France).[8] The geographical extent of our study is constrained by the spatial coverage of our temperature data. We present in Table 1 the share of households residing in geographic units covered by our temperature data. This proportion is close to 60% in Paris, Lyon, Bordeaux, and Montpellier, while Lille, Nantes, and Strasbourg exhibit proportions around 55%. Conversely, Marseille and Nice proportion slightly falls below 50%.

Table 1: Population covered in urban areas based on our temperature data

City rank	City	All households	Covered households	%
1	Paris	5,406,728	3,341,134	62
2	Lyon	1,022,642	588,495	58
3	Marseille*	789,463	384,236	49
5	Lille**	518,648	285,195	55
6	Bordeaux	584,924	348,632	60
7	Nice	474,448	218,401	46
8	Nantes	440,485	248,275	56
9	Strasbourg**	357,005	188,956	53
15	Montpellier	296,444	181,715	61

Source: Fideli, authors' calculations. Note: We define cities as the set of municipalities that belong to the urban area defined by INSEE as of 2010 ; see https://www.insee.fr/fr/information/2115011. *Marseille belongs to the Aix-Marseille urban area; we only have data for Marseille. **French part of the urban area.

Temperature. We use temperature data provided by the Copernicus Climate Change Service that contains inputs to compute air temperature differences within cities and their surrounding rural areas.[9] Importantly, temperature corresponds to the modeled temperature in the street two meters above the ground, not to the indoor temperature in dwellings.[10] Temperature differences are available every hour at a 100m*100m spatial resolution. The temperatures are generated by the ECMWF's UrbClim climate model incorporating meteorological data and detailed terrain descriptors, including land use, soil sealing, and vegetation.[11] Land use classification (rural/urban) comes from Corine Land Cover.

We restrict our analysis to year 2017. Indeed, temperature data are available between 2008 and 2017. As there were no major heatwave during this period, we focus on the last

[8]We have data on nine French cities, eight of them belongs to the tenth most populated cities in France (INSEE 2016); Montpellier is only ranked 15th.

[9]See data and documentation on https://forum.ecmwf.int/t/the-new-climate-data-store-beta-cds-beta-is-now-live/3315.

[10]Experimental, one-off temperature measurements can be carried out by thermal sensors on board aircraft (aerial thermography) or cars travelling over or in a given area. These data only concern a restricted area. Moreover, surface temperature strongly depends on the building material and cannot be directly interpreted in terms of public health, unlike air temperature measurement.

[11]For further details on the ECMWF's UrbClim climate model, see https://confluence.ecmwf.int/display/CKB/Climate+variables+for+cities+in+Europe+from+2008+to+2017+documentation.

year available, 2017. These differences in the UHI index serve as a lower bound, as the exacerbation of climate change will intensify heatwaves and the urban heat island effect. Indeed, the UHI effect is highly positively correlated with absolute temperatures (Section 2.1). Differences of tenths of a degree in the UHI index in 2017, which are not necessarily significant in terms of public health per se, serve as a proxy for larger discrepancies during future heatwaves in the years to come.

Following the data documentation, we compute a UHI index for the summer of 2017, at night. First, we calculate the daily minimum temperature for each tile. We notice that mininimum temperatures typically occur during the night. We then calculate the difference between these minimums and the average minimum temperature in the countryside. Finally, we define our UHI index as the average of these daily differences over the summer (May to August).[12] A higher UHI index does not indicate a higher absolute temperature but a higher temperature than in surrounding rural areas.[13]

Our results are robust to alternative definitions of the UHI index. In particular, they remain robust when defining the UHI index not on all summer nights, but only on particularly hot summer nights at national level in 2017. Additional figures are available upon request.

Vegetation. We collect satellites images from Sentinel with a 10m resolution.[14] Images are taken every 5 days since January 2017. Sentinel provides an already coded filter to select the least cloudy pixel. We restrict to the year 2017 to be consistent with our temperature data and to the months May and June, as we believe vegetation is at its greenest at this period of the year.

We process our satellite images. Each pixel is defined as a combination of red, blue, and green components. We define a pixel as green if its green component is greater than 1.1 times its red component and 1.1 times its blue component. We check that this definition includes well-known green spaces in different cities (see Appendix A.3 for the Paris example) and corresponds to statistics provided by local actors, such as the Atelier parisien d'urbanisme (Apur) in Paris. Our results are robust to changes in this arbitrary threshold. We define our vegetation index as the share of green pixels per tile of 100m x 100m.

[12] We calculate three alternative UHI indexes, using daily maximums and minimums in summer and in winter. Summary statistics for all UHI indexes are available in Table 6 in Appendix A.2.

[13] Our UHI indexes follow the same spatial patterns than in Mapuce, i.e. higher temperatures in dense city centers. However, Mapuce's UHI measure is higher in average, with for instance a maximum of +6.4°C in Paris' urban areas compared to rural ones, while we only have a +4.3°C maximum difference. Besides, Mapuce's ranking of most exposed cities results in Paris being well above other cities, while the city of Nice (maximum +5.01°C) shows the highest values in our data, closely followed by Marseille (maximum +4.8°C) then Paris. Those differences can be explained by climate variables used as inputs for UHI temperature simulation. For instance the proximity to the coast, absent from ECMWF's UrbClim model but present in Mapuce, plays a mitigating role and might explain the difference in temperatures for Nice. For further details on the Mapuce project and the underlying model, see https://www.umr-cnrm.fr/ville.climat/spip.php?article285.

[14] Data are available on https://docs.sentinel-hub.com/api/latest/data/sentinel-2-l2a/.

Distance to the city center and the nearest hospital. Cities are made up of municipalities. We define the city center as the population-weighted barycenter of the municipalities, that we calculate using the population and the coordinates of the municipalities' town halls. We then use the coordinates of the dwellings to calculate their distance from the city center. Utilizing a publicly available database of French facilities,[15] which includes the coordinates of each medical facility in France, we calculate the distance between each dwelling and its nearest hospital or emergency medical center.[16]

Households and dwellings. We rely on Fideli,[17] an exhaustive and administrative dataset, on French residential dwellings, individuals and households for the year 2017. The database provides key information on households, in particular their size, their equivalized disposable income in € per consumption unit (called hereafter *income in € per CU*), the age of their members.

The database links each French household to the dwelling in which it lives (its main residence). Dwellings are geolocated by their coordinates, allowing us to map them to the tile they belong to. The database provides the surface area of each dwelling in square meters, whether it is an apartment or a house, and the floor number if it is an apartment. We also know the maximum number of floors in the building of the dwelling.[18] We use the surface area to construct a measure of residential density at the tile level by dividing the total surface area of all residential dwellings in a tile by the tile surface (10,000 square meters). We use the maximum number of floors in buildings to construct a measure of residential building height at the tile level by averaging the maximum number of floors in residential buildings in a tile, weighted by the number of dwellings in each building. We also know the construction date of dwellings, which we use to create three categories: constructed before 1947, between 1948 and 1980, and after 1981. These thresholds are relevant for several reasons. The post-war period saw the development of the first public housing construction programs, under pressure from the baby boom and the rural exodus (Laferrère 2004), often resulting in buildings of lower quality. Following the oil shocks of 1973 and 1979, 1980 saw the end of an era of cheap energy and the development of more stringent insulation requirements, leading to improved housing quality in new buildings (Dupont 2018). The density, height, and period of construction of residential buildings in a tile serve as proxies for its urban form. Urban forms are associated to different exposure to UHI as the primary cooling factor at night is the presence of a clear sky. For example, dense and compact forms, which see little sky and characterize the centers of larger cities, have low cooling capacity at night, whereas peri-urban fabric, characterized by dispersed urban forms, cools effectively at night (APUR 2012).

[15] Permanent database of facilities, https://www.insee.fr/en/metadonnees/source/serie/s1161.

[16] We do not collect data on "cool islands", which can include parks, gardens, swimming pools and water features, as well as buildings such as museums, places of worship, "naturally cool" monuments and air-conditioned shopping malls and libraries. We focus our data collection on those that explained night-time temperature, which is the main criterion in terms of public health.

[17] Fideli is a set of housing and individual demographic files, see for example http://doi.org/10.34724/CASD.295.2554.V1.

[18] We do not use data relative to dwelling thermal insulation, as our variable of interest is outdoor street temperature, not indoor temperature. Unlike the age and size of the building, the thermal insulation of a dwelling does not provide any information on urban form or external elements that could explain the outside temperature.

2.3 Mapping our datasets

We match our tile-level databases with our individual-level databases, assigning the coordinates of each residential building to its corresponding tile. We produce two databases, one at household level, the other at tile level. Table 7 in Appendix A.4 presents our variables definition in the two databases. Our key variables are either household-related (income, whether one member of the household is above 65 years old or under 10, whether the household owns its dwelling, secondary dwellings, whether the households lives in a flat, and if so the highest floor of its building, residential building height and period of construction, and distance to the city center and to the nearest hospitals), or either tile-related (UHI and vegetation indexes, residential density). Household-related variables are aggregated at the tile level in the tile database, by sum (for residential density) or average (for residential building period of construction and height, distances, income, age, ownership status). Tile-related variables are linked to households based on their residential tile in the household database.

2.4 Summary statistics

Table 2 provides descriptive statistics for the variables in our two databases. In total, there are 5,785,039 households and 180,794 tiles.

UHI index. As UHI index is correlated with absolute temperatures (Section 2.1), we observe higher UHI indexes in the cities of the south of France (see Figure 23b in Appendix A.7 for a comparison of cities). For this same reason, differences of tenths of a degree in the UHI index in 2017 serve as a proxy for larger discrepancies during future heatwaves in the years to come. Indeed, we average over summer months and not only during heatwaves to calculate the index and we calculate it for the year 2017 with no major heatwave.

Households are concentrated in areas more exposed to UHI. Comparing means across tiles and across households shows that households are disproportionately concentrated in tiles close to city centers characterized by limited greenery, high residential building density and height, and consequently higher UHI exposure. As a result, the average UHI exposure across households exceeds the one across tiles with reduced dispersion.

In these "hot" tiles near the city center, households have a lower income, are younger, far less numerous to be homeowners, and slightly more numerous to have a secondary dwelling. These results illustrate the needs of job proximity for working people, the difficulty in buying a primary home in city centers, and the need of escaping downtown with a secondary dwelling for those who can afford one.

The appropriate database to study climate inequality. As households are not evenly distributed across tiles, it is particularly relevant to exploit our household database to measure UHI exposure among households depending on their income. Indeed, the average standard of living shows a higher dispersion across households than across tiles, because averaging across tiles reduces the disparities by canceling inherent heterogeneity within tiles.

Maps. We map UHI indexes in Figures 1 and 2 (Panel (a)) for Paris and Lyon, respectively.[19] We plot the UHI index for summer, at night, at the tile level, in degrees Celsius difference with the surrounding rural area (blank spaces in figures). The same scale is used in all maps for different cities, in order to represent both intra- and inter-city variation in the UHI index. All figures show a positive correlation between the UHI index and the proximity to the center of the city.

We also plot our vegetation index, as proportion of green pixels in each tile, in Panels (b) of the same figures,[20] and illustrate the inverse relationship between temperature and vegetation. This relationship is expected as it follows directly from the climatic model (UrbClim) our temperature index comes from. Finally, we plot density by municipality in Panels (c), measured as the ratio of housing surface over the municipality, and mean income by consumption unit in Panels (d). Density patterns follow the monocentric model, with lower values further from the city center. Lastly in panel (d), we plot the average income per municipality. In the city of Paris, the central municipality is among those with the highest average income, which is not the case for Lyon.

[19] Maps for the rest of the cities are in Appendix A.5, Panels (a) of Figures 15 to 21.

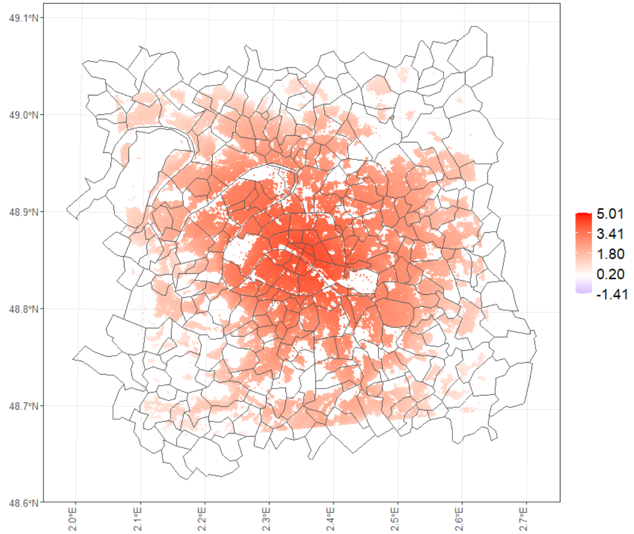
[20] Even if known green spaces in different cities are well represented by the vegetation index, parks and gardens appear in white in the UHI and vegetation maps, because these maps only display grid cells where people live.

Table 2: Summary statistics

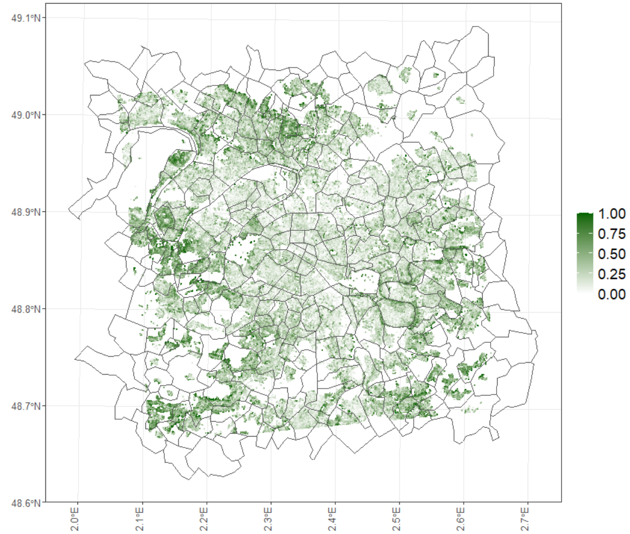
Variable	Household database		Tile database	
	Mean	Sd	Mean	Sd
UHI index (in °C difference)	2.8	1	2.1	0.99
Distance to city center (in m)	8,711	5,335	10,486	5,642
Distance to nearest hospital (in m)	931	1,212	2,042	2,082
Residential buildings density	0.69	0.71	0.22	0.31
Residential buildings period of construction				
% constructed before 1947	30		27	34
% constructed after 1981	38		34	37
% households living at highest floor (flats only)	6.2		18	27
Residential building height (number of floors)	3.9	4	2.3	2.1
Vegetation index (in %)	21	17	29	22
Households characteristics				
Income*	27,738	44,062	30,909	41,975
% households with one member aged less than 10	18		18	17
% households with one member aged more than 65	28		33	24
% households owners of their dwelling	46		68.4	33.8
% households in social housing	21		8.9	25
% households renting their dwelling (private sector)	31		23	27
% households owning a secondary dwelling	8		6.6	10
% households living in a house	23		62	42
% households living in a flat	77		38	42
Number of observations	5,785,039		180,794	

* Average annual standard of living (in € by consumption unit)

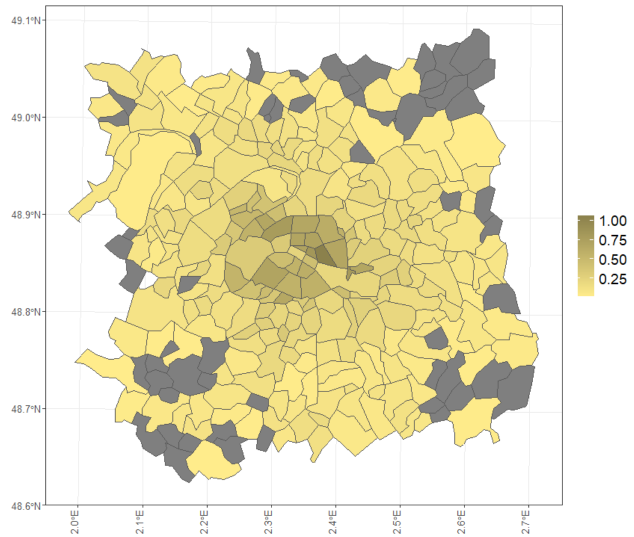
Figure 1: Paris



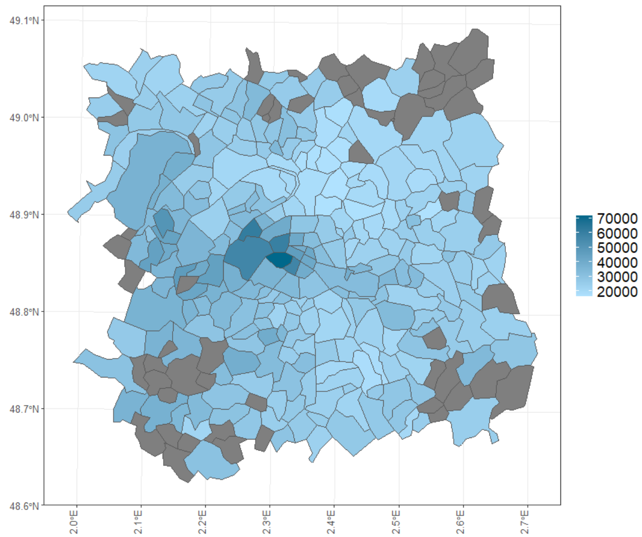
(a) UHI index (Δ degree Celsius)



(b) Vegetation (%)



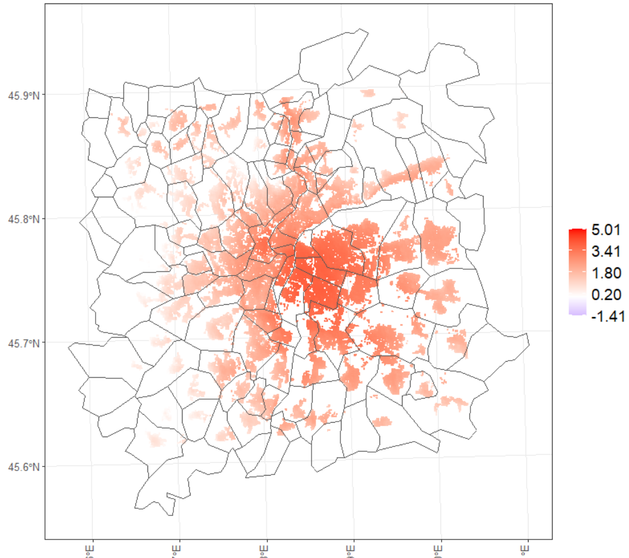
(c) Density



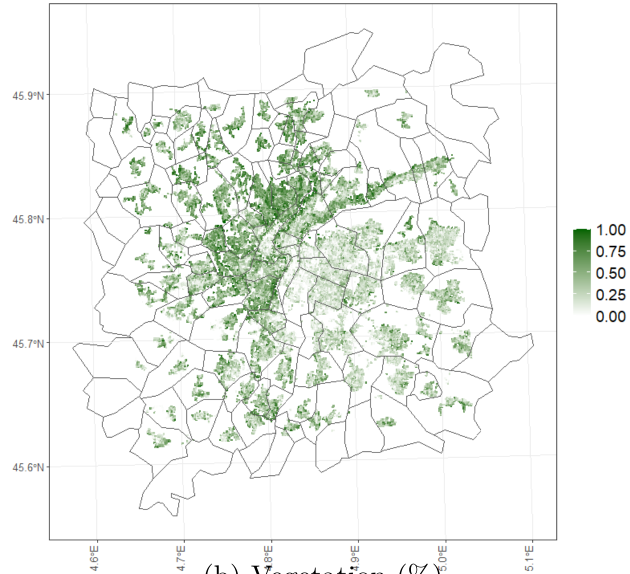
(d) Income (€ per CU)

Note: We present four maps of the city of Paris. The grey borders represent all the city's municipalities. Maps (a) and (b) represent, at tile level, the UHI index in degrees Celsius difference with the surrounding countryside and the vegetation index in percentage of green pixels. Maps (c) and (d) represent, at municipal level, the density of residential buildings, calculated as the sum of the surface area of dwellings located in the tile divided by its surface area, and the average annual household income in € per consumption unit. Data dissemination rules to protect households confidentiality only allow us to present these two variables for municipalities with more than 5,000 inhabitants. This explains the grey municipalities in Maps (c) and (d). Note however that we do not have this type of restriction in our two databases. Conversely, households living in white tiles on Maps (a) and (b) are not covered by our databases.

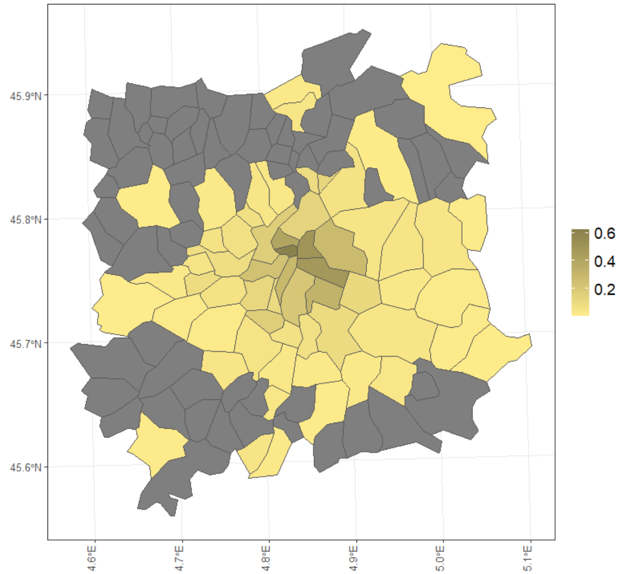
Figure 2: Lyon



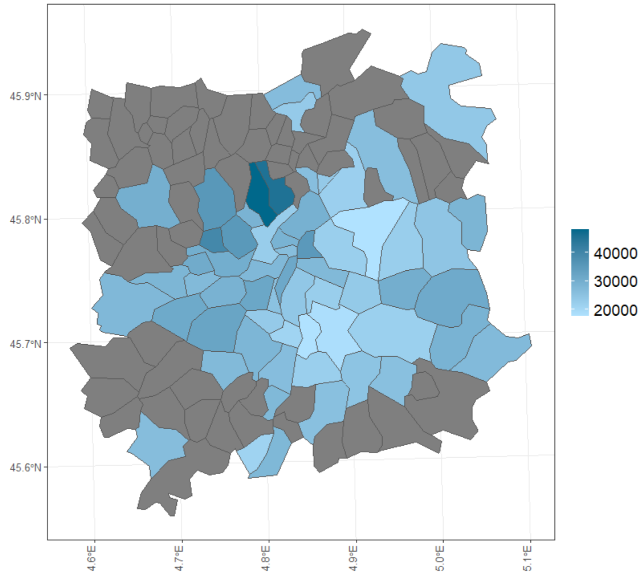
(a) UHI index (Δ degree Celsius)



(b) Vegetation (%)



(c) Density



(d) Income (€ per CU)

Note: We present four maps of the city of Lyon. The grey borders represent all the city's municipalities. Maps (a) and (b) represent, at tile level, the UHI index in degrees Celsius difference with the surrounding countryside and the vegetation index in percentage of green pixels. Maps (c) and (d) represent, at municipal level, the density of residential buildings, calculated as the sum of the surface area of dwellings located in the tile divided by its surface area, and the household average annual income in € per consumption unit. Data dissemination rules to protect households confidentiality only allow us to present these two variables for municipalities with more than 5,000 inhabitants. This explains the grey municipalities in Maps (c) and (d). Note however that we do not have this type of restriction in our two databases. Conversely, households living in white tiles on Maps (a) and (b) are not covered by our databases.

3 Unequal exposure to urban heat island with respect to income

In this section we measure UHI exposure across the households depending on their income in the major French cities.

3.1 Urban spatial sorting and UHI exposure

Two types of cities: the richest households are either located downtown or in the suburbs. In Figure 3, we present the average distance to the city center by groups of households classified by decile of national income in various cities. In each city, the different national deciles are well represented (Figure 22 in Appendix A.6). This allows us to classify cities into two groups based on their spatial sorting. The first group, comprising Paris, Bordeaux, Lille, and Nantes, is presented in Panel (a). In these cities, the distance from the city center by income follows a bell-shaped curve, meaning households at the extremes of the income distribution reside closer to the city center than those in the middle. The second group, comprising Lyon, Montpellier, Marseille, Strasbourg, and Nice, is presented in Panel (b). In all these cities except Nice, the distance to the city center increases with income, i.e., the wealthier the household, the further it lives on average from the city center. In Nice, the distance to the city center decreases rather than increases with income, but varies little compared to most of the other cities. These low variations are likely explained by specific geographical constraints posed by the sea on one side and surrounding mountainous terrain on the other. We choose to keep Nice in the second group of cities because it has a similar UHI pattern to the cities in this group.

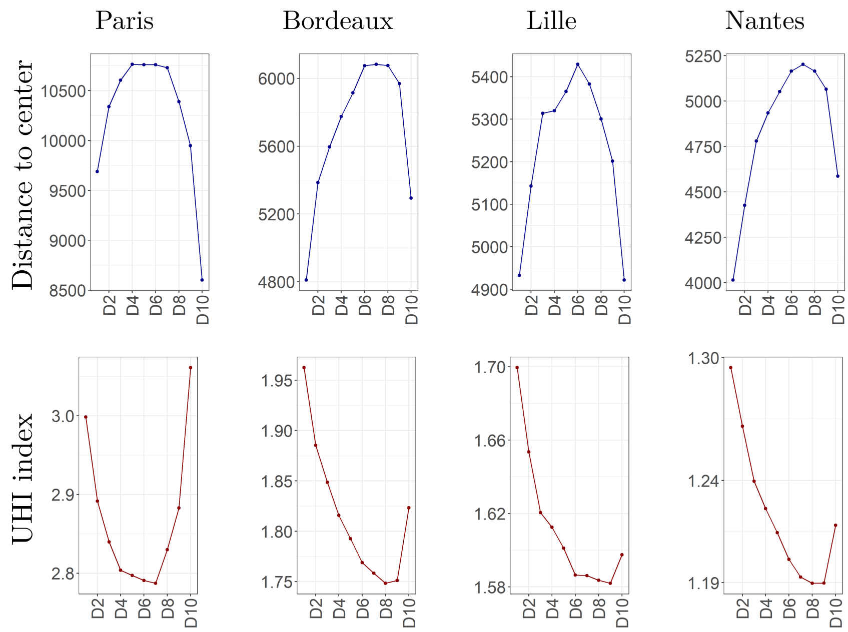
The question of spatial sorting within cities has long been discussed in the urban economics literature. Brueckner et al. 1999 propose an amenity-based theory, drawing on the monocentric model by Alonso 1964 and Muth 1969, to explain the existence of two types of cities: one where wealthy households live downtown, and the other where they live in the suburbs. Whether a city belongs to the first or second type depends on the relative amenity advantage of the center over the suburbs. Urban amenities underlying this theory fall into three groups: historical (monuments, buildings, parks), modern (restaurants, theaters, gyms, etc.), or natural (rivers, hills, coastline).

Until the 1980s, most American cities belonged to the second group, as wealthy households were attracted to the suburbs. However, there has been a significant shift in urban living trends in US cities in recent decades. Higher-income individuals have increasingly moved back into urban cores, with the propensity for households to live downtown following a U-shaped pattern with respect to income (Couture et al. 2024). Couture and Handbury 2023 provides a comprehensive review and explores channels that explain this reversal. This phenomenon is mostly driven by younger graduates seeking proximity to non-tradable services like restaurants and nightlife (Couture and Handbury 2020). Rising incomes for the highly skilled and later family formation have made urban life more appealing to the young and educated. Their higher incomes and more valuable time have made shorter commutes desirable, while their greater financial capacity has allowed them to enjoy city-center amenities such as bars and restaurants. These amenities have provided opportunities for networking, friendships, and encounters, particularly popular with wealthier, single, and childless individuals. As none of these channels are related to urban heat islands, we are confident in taking the spatial sorting of households as a given in this paper, assuming that UHI was not a factor considered by households in their location choices in 2017. This is an assumption that will need to be revisited in the coming years as climate change intensifies.

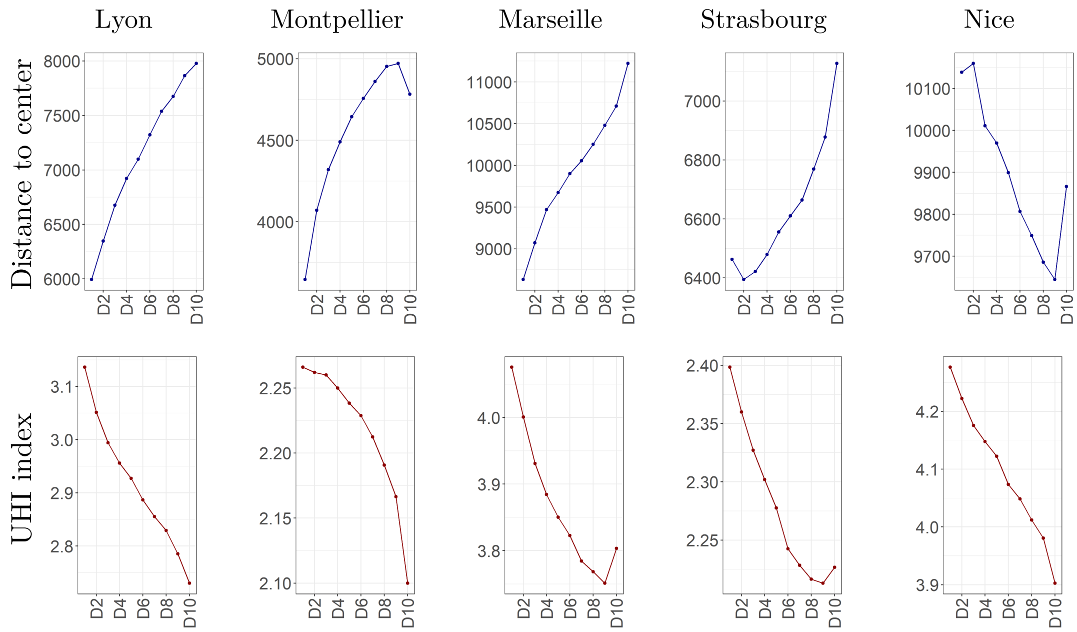
The exposure to UHI with respect to income is the inverse mirror image of the spatial sorting in the city. In Figure 3, we also present the average UHI index by income decile across cities. In cities belonging to the first group, where affluent households live on average close to the city center, the average UHI index is U-shaped with respect to income. This U-shape is particularly pronounced in the city of Paris, it is indeed the only city where the households most exposed to UHI are the wealthiest. In Bordeaux, the UHI curve decreases until the 8th decile before sharply increasing for the last decile, exceeding the UHI value of the 5th decile. In Lille, the UHI index decreases until the 6th decile, experiences minimal variation until the 9th, and then increases in the final decile to almost match the UHI value of the 5th decile. In Nantes, the UHI index decreases until the 8th decile, remains steady for the 9th, and then sharply increases to exceed the UHI value of the 5th decile. Table 3 displays the amplitude of the UHI index within cities. Nantes and Lille show a small UHI amplitude between the most and the least exposed deciles, with a difference of 0.11°C and 0.12°C respectively, compared to Paris (0.27°C) and Bordeaux (0.21°C). UHI inequalities do not follow density inequalities, as Paris has a very small amplitude (0.07) and Nantes has the highest (0.27) in this group of cities (Table 3). Figures 23b and 23d in Appendix A.7 show UHI and density amplitudes of cities by income decile.

In the second group of cities, where affluent households live on average further away from the city center, the UHI index decreases with income. The cities exhibiting the greatest inequality, where the amplitude is maximal, belong to the second group: Lyon (0.41°C), Nice (0.37°C), and Marseille (0.32°C). In contrast, cities with the smallest amplitude belong to the first group: Lille (0.12°C) and Nantes (0.11°C). In this second group as in the first one, UHI inequalities do not follow density inequalities (Table 3, Figures 23b and 23d in Appendix A.7). Finally, this second group includes cities located in the south of France (Nice, Marseille) with higher average UHI index (Section 2.1, Figure 23b in Appendix A.7).

Figure 3: Distance to city center and urban heat island index by income across cities



(a) Distance to city center is bell-shaped with respect to income; UHI index has a U-shaped relationship with income.



(b) Distance to city center is increasing with income; UHI index has an inverse relationship with income.

Note: This graph presents the average distance to the city center by national income decile across cities in blue, and the average UHI index (for summer nights) of households in red. The distance to the city center is measured in meters, while the UHI index is expressed in degrees Celsius differences with surrounding countryside. Scales are city-specific. We present all cities on a same scale in Figures 23a and 23b in Appendix A.7. We categorize cities based on the shapes of the distance to the city center and UHI curves. In Panel (a), we present cities whose distance to the city center by income follows a bell-shaped curve, and whose UHI index follows a U-shaped curve. In Panel (b), we show cities where the UHI index decreases with income and where distance to the city center increases, except in Nice where distance to the city center rather decreases. See Table 3 for the amplitude of distance to the city center and UHI index in each city.

3.2 Wealthier households live in greener, less dense neighborhoods but, depending on the city group, they choose older or newer neighborhoods

We now explore the relationship between income and vegetation or residential buildings characteristics (density, height, period of construction) in the neighborhood of residence.

In most cities, on average, wealthier households live in greener, less dense neighborhoods with lower buildings. The wealthier the household, the greener the neighborhood on average, in all cities with minor exceptions in Nantes and Montpellier (Figure 4).[21] Paris has the lowest amplitude in terms of vegetation across income deciles among the cities, and Lille the highest (Table 3). The wealthier the household, the less dense the neighborhood on average across all cities, except Paris, where density by income follows a U-shaped curve but with a low amplitude, at least twice lower than in the other cities (Table 3). Finally, wealthier households tend to reside in neighborhoods with lower building heights on average, in all cities, with minor exceptions in Montpellier and Paris (Figure 5).[22]

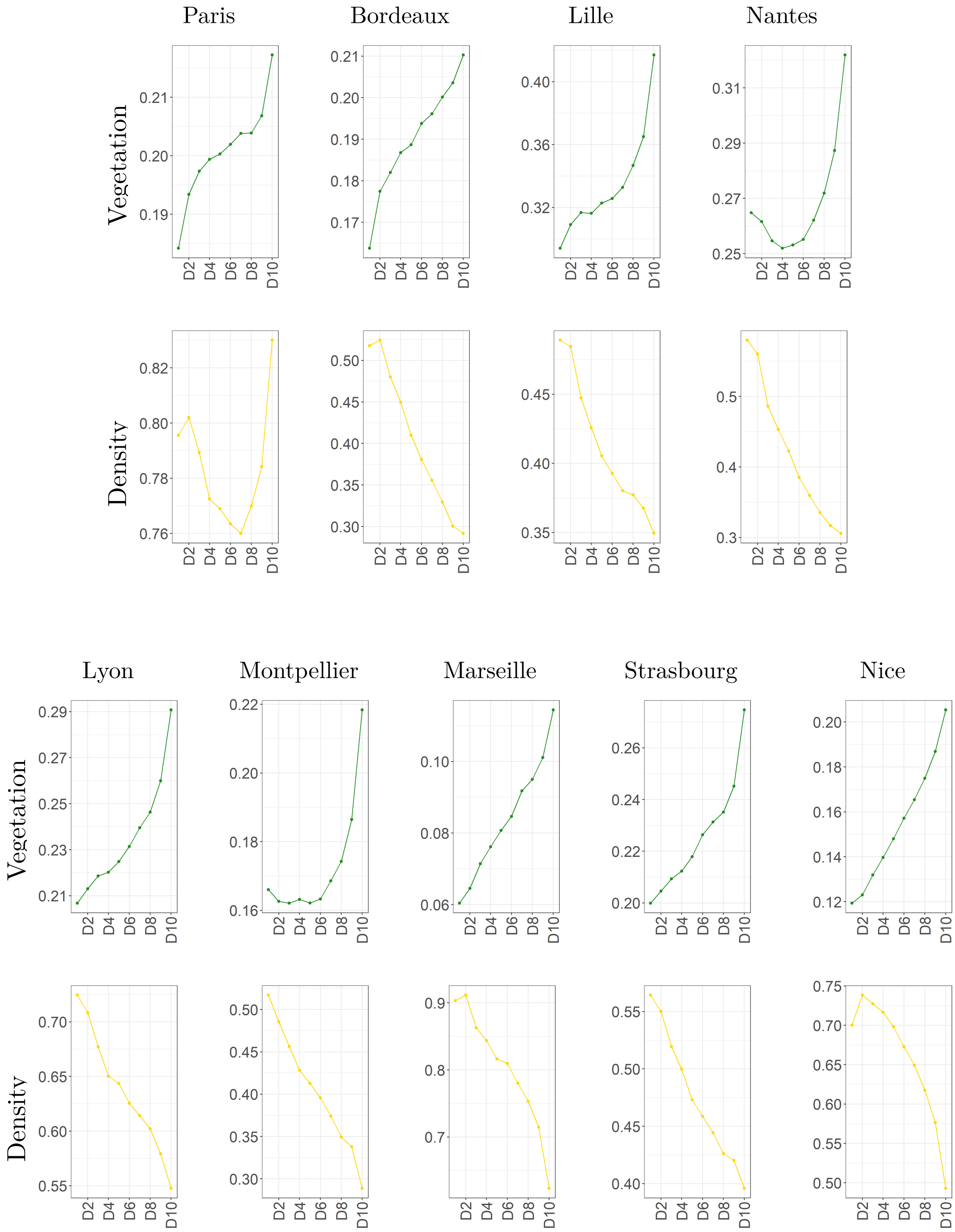
In the first group of cities, wealthier households choose older neighborhoods, while in the second group, they prefer newer neighborhoods. The two groups of cities are essentially distinguished by the location choices of affluent households regarding older or newer neighborhoods. Indeed, in all cities except Lille, the share of old buildings in the neighborhoods of residence roughly resembles a U-shaped curve with respect to income (Figure 6) but, in the first group of cities, wealthier households are more likely to live in older neighborhoods, whereas, in the second group, low-income households are more likely to do so. Besides, in the second group, wealthier households prefer newer neighborhoods on average, whereas in the first group, except in Lille, the share of recent buildings in the neighborhoods of residence follows a bell-shaped curve with respect to income.[23]

[21] In Nantes, the vegetation index in the neighborhood of residence follows a predominantly flat U-shaped curve for the first 7 deciles, then sharply increases for the last 3 deciles. Similarly, in Montpellier, the vegetation index experiences a slight decrease between the first and second deciles, remains relatively stable up to the 6th decile, and then sharply rises (Figure 4).

[22] In Paris, the curve shows an increase for the top income decile, and in Montpellier, there is a slight increase after the 6th decile. However, these are the two cities where the variation in average building height across income deciles is the lowest (Table 3).

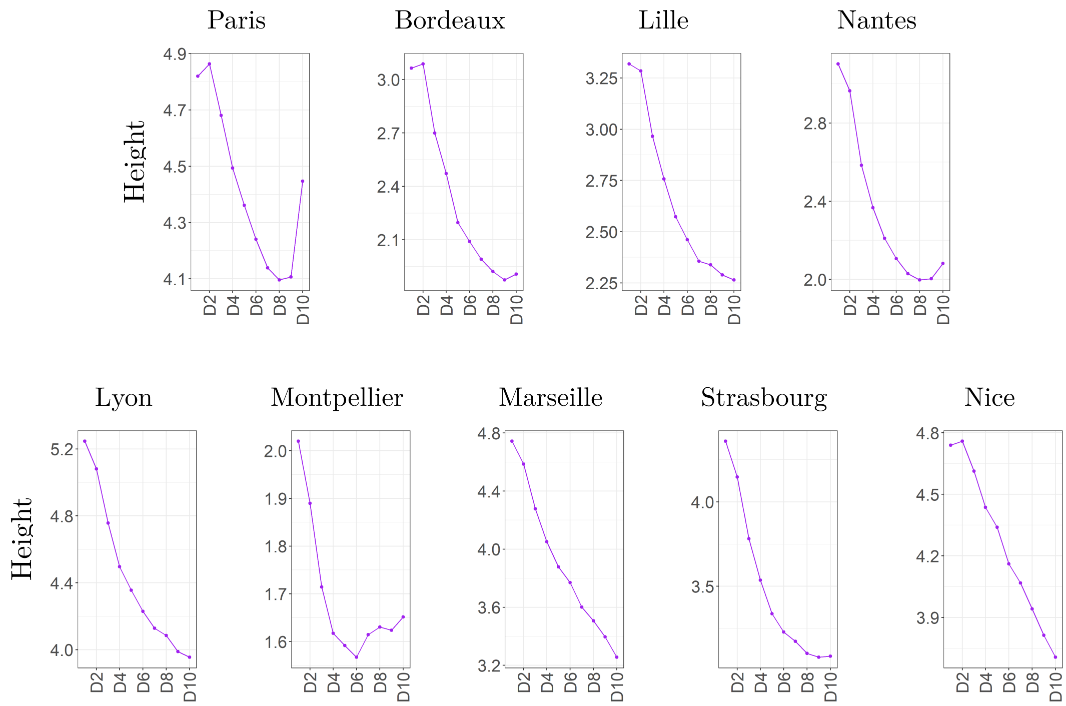
[23] Paris exhibits the least variations in the share of recent constructions across income deciles, likely because of fewer new constructions (Table 3).

Figure 4: Vegetation and residential density in the neighborhood of residence, by income across cities



Note: This graph presents the vegetation index and the density of households by national income decile across cities. Scales are city-specific. We present all cities on a same scale in Figures 23c and 23d in Appendix A.7. See Table 3 for the amplitude of vegetation index and density in each city.

Figure 5: Height of residential buildings in the neighborhood of residence, by income across cities



Note: This graph presents the average height of residential building in the tile of residence of households, by income decile. Scales are city-specific. We present all cities on a same scale in Figure 24a in Appendix A.7. See Table 3 for the amplitude of the variable in each city.

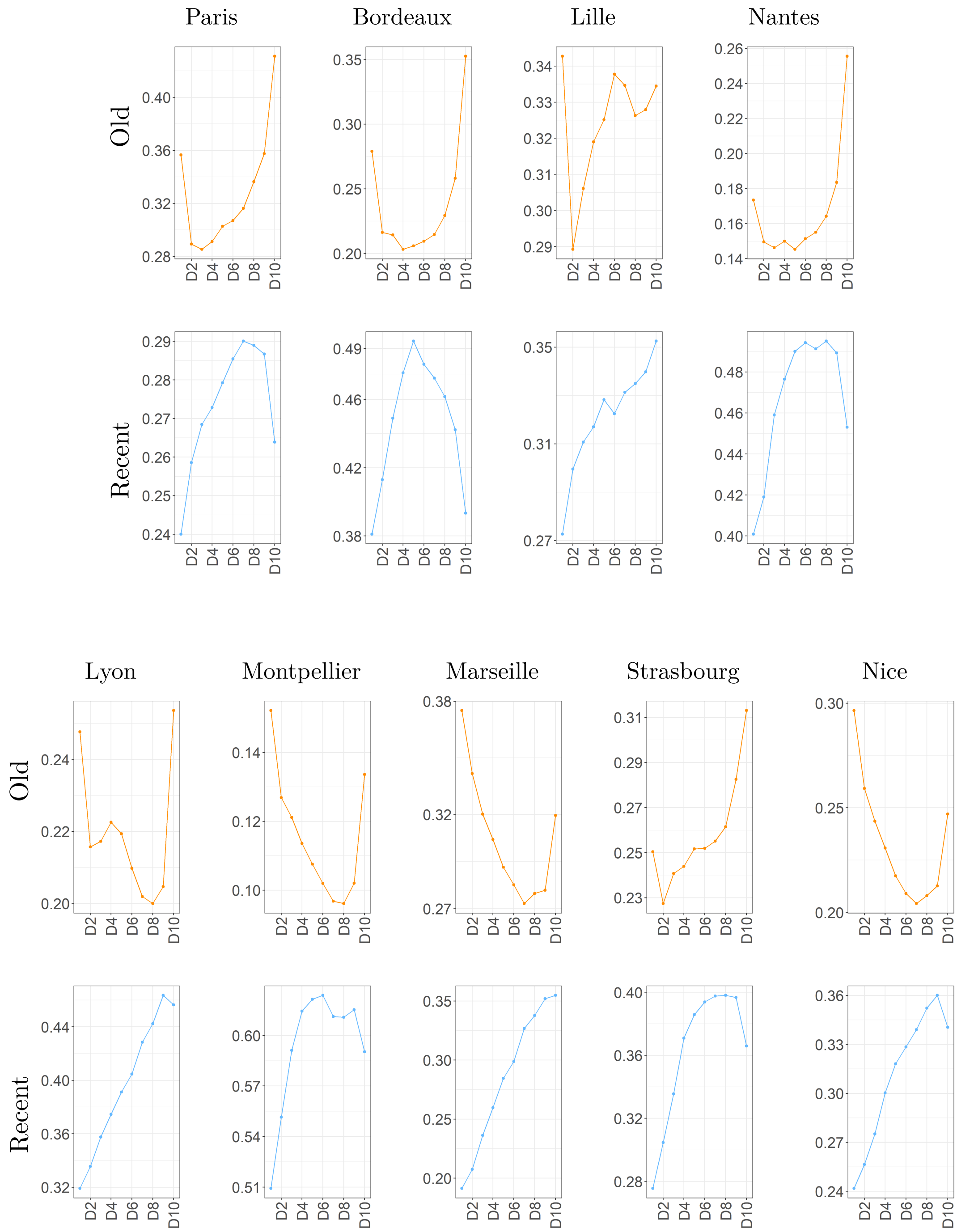
Table 3: Amplitude of different variables calculated by income deciles

	Distance to city center (meters)	UHI index night summer (°C difference)	Vegetation (pp)	Density (no unit)	Height (average floor number)	Construction before 1947 (pp)	Construction after 1981 (pp)
Paris	2161	0.27	0.03	0.07	0.77	0.17	0.04
Bordeaux	1272	0.21	0.05	0.23	1.21	0.14	0.12
Lille	507	0.12	0.12	0.14	1.05	0.04	0.07
Nantes	1188	0.11	0.07	0.27	1.1	0.1	0.1
Lyon	1982	0.41	0.09	0.18	1.29	0.07	0.12
Montpellier	1324	0.17	0.05	0.23	0.45	0.04	0.13
Marseille	2589	0.32	0.05	0.29	1.49	0.07	0.13
Strasbourg	732	0.19	0.07	0.17	1.28	0.1	0.11
Nice	515	0.37	0.09	0.25	1.05	0.06	0.07

Note: pp means percentage points.

Lecture: In Paris, the difference in distance to the city center between the income decile living farthest away on average and the income decile living closest on average is 2,161 meters.

Figure 6: Share of old or recent residential buildings in the neighborhood of residence, by income across cities



Note: This graph presents the proportion of households residing in buildings constructed after 1981 (classified as *recent*) or before 1947 (classified as *old*) by income decile across cities. Scales are city-specific. We present all cities on a same scale in Figures 24b and 24c in Appendix A.7. See Table 3 for the amplitude of the two proportions in each city.

3.3 Main sources of unequal exposure to UHI by income

In order to guide public policy interventions, we aim to identify the primary sources of unequal exposure to UHI by income across cities. To achieve this, we first conduct a straightforward econometric analysis where we regress the UHI index in each tile against relevant variables in all cities. This enables us to identify key contributors to UHI exposure and to measure their impact for each city in order to find city-specific levers for action. Then, we measure their contributions to the unequal exposure to UHI by income in each city.

Identifying the key contributors to UHI exposure. First, we conduct a straightforward econometric analysis where we regress the UHI index in each tile against relevant variables. This approach effectively linearizes the meteorological model used to generate temperature data. As temperature is measured two meters above the ground, we only consider variables that can explain outside temperature and not indoor ones (Section 2). We run the following regression for all cities:

$$UHI_{t,c} = \alpha_v V_{t,c} + \beta_d dens_{t,c} + \gamma_{b1947} X_{t,c}^{B1947} + \gamma_{a1981} X_{t,c}^{A1981} + \zeta_h H_{t,c} + \nu dist_{t,c} + C_c + \epsilon_{t,c} \quad (1)$$

$UHI_{t,c}$ is the UHI index of tile t in city c, $V_{t,c}$ is the vegetation index, $H_{t,c}$ the average building height, $X_{t,c}^{B1947}$ and $X_{t,c}^{A1981}$ the share of residential buildings constructed before 1947 or after 1981. $dens_{t,c}$ is the residential building density, $dist_{t,c}$ the distance to the city center. We add city dummies C_c. Spatial autocorrelation is taken into account by clustering residuals at the municipality level. Table 4 presents the results of the regression analysis. Columns (1) to (5) display results with one of the following variables: vegetation, density, distance, height, and the share of old or recent residential buildings, respectively. In Column (6), we present the regression including all six variables.

Our simple method to linearize the climate model effectively identifies key contributors to UHI differences across tiles. First, all coefficients are significant at the 1% level. Second, these regressions exhibit high explanatory power despite the limited number of variables, with R^2 reaching 0.74 in Column (6).

Our variables on vegetation and residential buildings (density, height, share of old/recent buildings) capture part of the heterogeneity of urban morphology across tiles, explaining some of the differences in UHI exposure. As expected with the phenomenon of evapotranspiration and the albedo effect,[24] the UHI index is negatively correlated with the vegetation index and positively correlated with residential building density and average height. Indeed, dense and compact forms have low cooling capacity at night (Section 2). In particular, a high share of old buildings is likely associated with ancient neighborhoods and narrow streets that trap heat, and hence is associated with high UHI exposure. This is why UHI exposure is positively correlated with the share of old residential buildings, and negatively correlated with the share of recent residential buildings. The multidimensionality of urban form cannot be represented solely by variables on residential buildings, as public buildings, firms, and roads also contribute to varying levels of UHI exposure.

[24] The albedo effect influences the amount of solar radiation absorbed or reflected by surfaces. Lower albedo materials such as asphalt absorb more heat and contribute to higher temperatures.

This is captured by the distance to the city center, as proximity to the center correlates with more roads, public buildings, and firms. As expected, UHI exposure is negatively correlated with the distance to the center.

Table 4: Regression of UHI night index in summer 2017 by tile characteristics

	Dependent variable: UHI index (°C)					
	(1)	(2)	(3)	(4)	(5)	(6)
Vegetation	-1.529***					-0.8914***
	(0.0892)					(0.0563)
Density		1.109***				0.2992***
		(0.0552)				(0.0347)
Distance			-1.275***			-1.043***
			(0.0463)			(0.0485)
Height				0.1483***		0.0355***
				(0.0101)		(0.0053)
Share construction before 1947					0.5937***	0.2648***
					(0.0468)	(0.0272)
Share construction after 1981					-0.1977***	-0.0419**
					(0.0293)	(0.0198)
City fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	180,794	180,794	180,794	180,611	180,794	180,611
R^2	0.39612	0.40612	0.67175	0.38120	0.34914	0.73903

Note: We regress the UHI index by the vegetation index, the residential density, the distance to the city center divided by 100 km, the height of residential buildings, and by the share of buildings constructed before 1947 and after 1981. Our units of observations are tiles. Standard errors are in parentheses, clustered by municipality. Statistical significance markers: *p<0.1; **p<0.05; ***p<0.01

Levers of public actions for each city. As the impact of key contributors to UHI may vary across cities, we further decompose the difference in UHI exposure across tiles within cities by running a modified version of Equation 1, interacting each explanatory variable with city dummies. Table 5 presents both the common effects of variables across all cities and their city-specific additional effects. We do not include the distance to the city center in this regression because, although it explains a significant part of the UHI differences across tiles, it is not in itself a lever for public action. The R^2 is above 0.5, lower than in Table 4 because distance is not included. As expected, cities located further south, Nice, Marseille, and to a lesser extent Montpellier and Lyon, are more exposed to UHI, while cities located further north and close to a sea or an ocean (Lille, Nantes) are less exposed.

We find that the cooling effect of vegetation is particularly marked and significant in explaining differences in UHI exposure in Nice and Marseille. The heating effect of height is especially marked in Paris, Nice, Lyon, and Marseille. The heating effect of the share of old residential buildings is particularly pronounced in Paris. The cooling effect of the share of recent buildings is notably significant in Lyon, Nice, Strasbourg, and Montpellier. There is no significant city-specific difference in the heating effect of density.

Contributions to the unequal exposure to UHI by income decile. We now explain and break down the differences in exposure by income decile. To do so, we build on the results of the last regression to quantify the contributions of vegetation, density, height, and the share of old/recent buildings to the unequal exposure to UHI by income decile. Contributions are calculated using the coefficients estimated in Table 5 with the average values of each variable by income decile across cities (given in Figures 4, 5, and 6). Each variable's contribution is normalized by subtracting its city-level mean, and the results are presented in Figure 7. Here is a concrete example illustrating how to interpret the contribution of a variable for a specific income decile and city: living in a neighborhood with a high share of old residential buildings is associated with high UHI exposure. In the city of Paris, households in the second income decile, on average, reside in neighborhoods with a lower share of old buildings. This contributes to their relatively lower exposure to UHI for these households *compared to other Paris households.*

As expected, building density, vegetation, and average building height contribute to a decreasing linear relationship of UHI exposure with income (Subsection 3.2). Here we are able to quantify and compare the contributions of these factors. We observe that in all cities density has a predominant impact on unequal UHI exposure and that except in Paris, it contributes to a decreasing relationship of UHI exposure with income. By this, we mean that density contributes to higher relative exposure for lower-income households and lesser relative exposure for wealthier households. Following density, vegetation and building height also play significant roles. Vegetation contributes to a decreasing linear relationship of UHI exposure with income in all cities. The effect is notably stronger in the second group of cities — Nice, Marseille, Lyon, and Montpellier — in order of importance. In contrast, it has a small effect in the first group of cities — Paris, Bordeaux, Lille, and Nantes. Except in Montpellier, building height similarly contributes to a decreasing relationship of UHI exposure with income in all cities. Its effect is particularly pronounced in Lyon, Marseille, and Nice, whereas it has almost no effect on contributions in Lille and Nantes.

Ultimately, as announced in Subsection 3.2, the period of residential building construction in neighborhoods partly explains the varied U-shaped in the first group of cities and decreasing curves of UHI exposure by income in the second one. The impact of the share of old residential buildings on UHI exposure relative to income follows a U-shaped pattern: in all cities, this variable positively affects both the lowest and highest income deciles, while the middle income brackets live in less old buildings and have a reduce UHI exposure. However, the magnitude of this effect and the location of the inflection point vary across cities. This U-shaped curve is notably pronounced in Paris, explaining part of the UHI U-shape curve with respect to income. It is also quite pronounced in Bordeaux. Conversely, the contribution of the share of recent buildings to UHI exposure decreases with income. This contribution is negligible in cities like Paris, Bordeaux, Lille, and Nantes (the first group), but substantial in cities such as Lyon and Strasbourg (the second group).

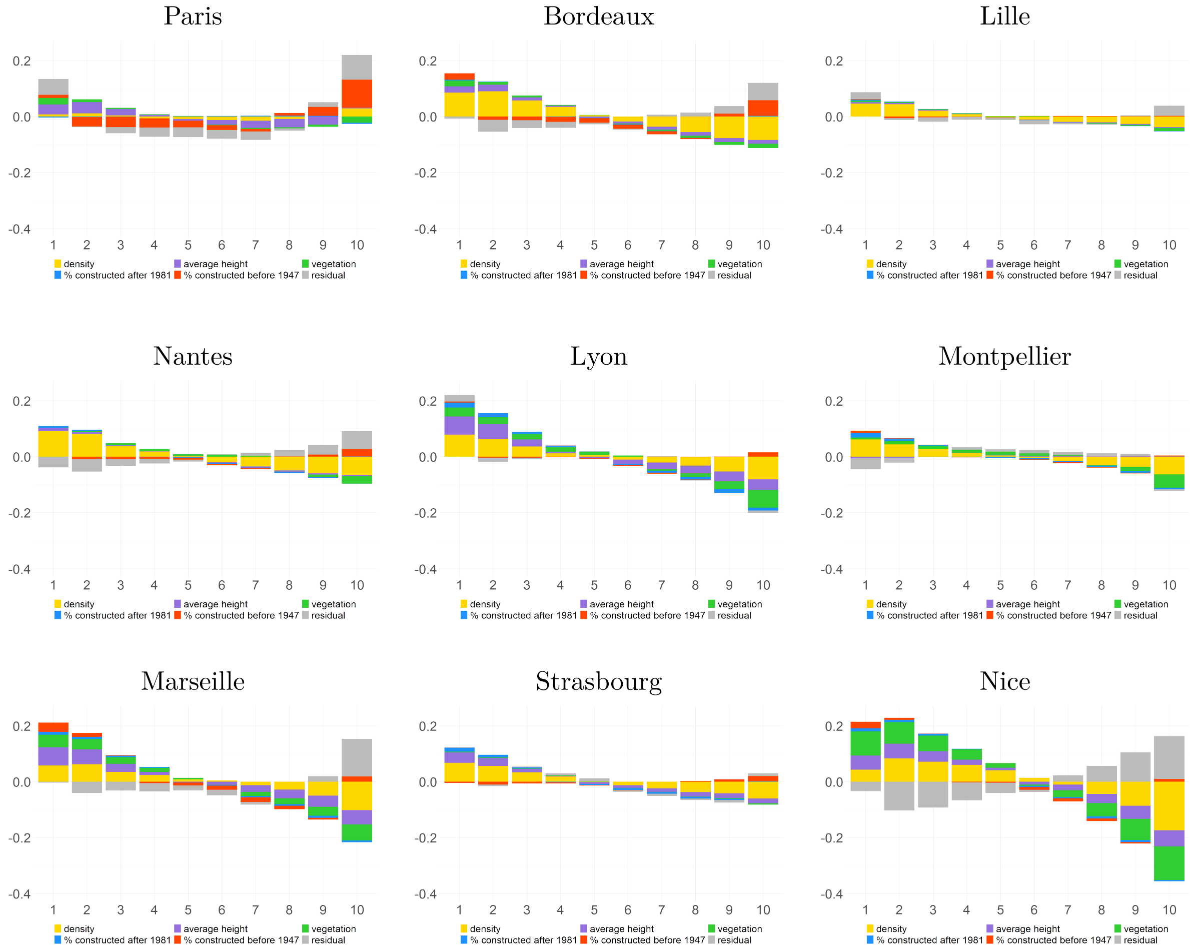
Table 5: Regression of UHI index by various factors interacted with city dummies

	Dependent variable: UHI index (°C)	
Vegetation	Paris	-1.373^{***} (0.089)
	Bordeaux	-0.772^{***} (0.074)
	Lille	-0.136^{***} (0.109)
	Nantes	-0.511^{***} (0.104)
	Lyon	-1.141^{***} (0.189)
	Montpellier	-1.076^{***} (0.161)
	Marseille	-1.892^{***} (0.357)
	Strasbourg	-0.102 (0.086)
	Nice	-2.403^{***} (0.228)
Density	Paris	0.626^{***} (0.038)
	Bordeaux	0.749^{***} (0.102)
	Lille	0.599^{***} (0.085)
	Nantes	0.576^{***} (0.074)
	Lyon	0.903^{***} (0.104)
	Montpellier	0.546^{***} (0.092)
	Marseille	0.570^{***} (0.125)
	Strasbourg	0.759^{***} (0.196)
	Nice	1.045^{***} (0.369)
Average height	Paris	0.090^{***} (0.007)
	Bordeaux	0.031^{***} (0.008)
	Lille	0.007^{*} (0.004)
	Nantes	0.013^{***} (0.004)
	Lyon	0.079^{***} (0.017)
	Montpellier	-0.017 (0.013)
	Marseille	0.078^{**} (0.020)
	Strasbourg	0.042^{***} (0.008)
	Nice	0.105^{***} (0.029)
Share construction before 1947	Paris	0.826^{***} (0.050)
	Bordeaux	0.524^{***} (0.080)
	Lille	0.189^{***} (0.038)
	Nantes	0.337^{***} (0.079)
	Lyon	0.291^{***} (0.072)
	Montpellier	0.247^{***} (0.080)
	Marseille	0.686^{***} (0.136)
	Strasbourg	0.292^{***} (0.038)
	Nice	0.555^{***} (0.144)
Share construction after 1981	Paris	0.165^{***} (0.0.36)
	Bordeaux	-0.044^{*} (0.024)
	Lille	-0.073^{**} (0.035)
	Nantes	-0.088^{***} (0.031)
	Lyon	-0.259^{***} (0.053)
	Montpellier	-0.179^{***} (0.045)
	Marseille	-0.131 (0.089)
	Strasbourg	-0.186^{***} (0.069)
	Nice	-0.253^{***} (0.096)
Paris		0.451^{***} (0.106)
Lille		-0.120 (0.117)
Nantes		-0.402^{***} (0.102)
Lyon		0.765^{***} (0.177)
Montpellier		0.797^{***} (0.117)
Marseille		1.578^{***} (0.207)
Strasbourg		0.290 (0.184)
Nice		1.720^{***} (0.360)
Bordeaux		*ref.*
Constant		1.456^{***} (0.082)
Observations		180,611
R^2		0.563

Note: We regress the UHI index by vegetation, density, height and the shares of buildings constructed before 1947 and after 1981. All explanatory variables are interacted with city dummies. Our units of observations are tiles. Standard errors are in parentheses, clustered by municipality. Statistical significance markers: *p<0.1; **p<0.05; ***p<0.01.

Furthermore, there are UHI exposure differences that cannot be explained by our five variables, as indicated by the residual variable's contribution. While its contribution is minimal in Lyon, Montpellier, and Strasbourg, it holds significance in Paris, Marseille, and Nice. Notably, the relative contribution of the residual increases with income. This phenomenon sufficiently alters the shape of the UHI exposure curve with respect to income for the first group of cities, but not for the second group. The omitted variables may include factors like the density of non-residential buildings (captured by the distance variable in Regression 4), or could be related to human activities such as the presence of retail establishments, restaurants, road traffic levels, or the prevalence of air conditioning usage. This last assumption is particularly relevant since the share of households that possess an air conditioning system is increasing with income (Subsection 4.2, Figure 10).

Figure 7: Contributions to unequal UHI exposure by income across cities



Note: This graph presents the contribution of each variable to the unequal UHI exposure by income across cities. This contribution is calculated as the product of the coefficient in Table 5 and the mean value of the variable for the decile (given in Figures 4, 5, and 6). We normalize variable contribution by subtracting their city-level mean.

3.4 Policy recommendation for actions at the city level

Targeting vegetation and building quality, but not density. While density exacerbates UHI effects and also air pollution (Champalaune 2020), it also plays a role in reducing greenhouse gas emissions from transport (Borck 2016; Thé et al. 2021) and limiting land artificialization. This dual impact makes determining the optimal level of density challenging for policymakers. Given this ambiguity, UHI mitigation policies can effectively target unambiguous levers such as increasing vegetation and improving building quality.

Fortunately, even when considering existing urban planning constraints, feasible solutions for cooling cities are numerous and their effects cumulative. Nature can be reintegrated into urban areas by removing waterproofing from pavements, planting trees, greening floors, facades, roofs, or uncovering rivers. Buildings and urban planning also play crucial roles. Integrating summer comfort into construction or renovation criteria, using light-colored cladding or white roofs to reflect heat, adapting to wind corridors, and building public fountains or shade houses can significantly mitigate the impact of heatwaves (Santamouris 2007).[25]

Beware of short- and medium-term regressive effects. Our paper shows that poor households are often the most exposed to UHI effects, residing on average in less green, denser, and taller neighborhoods. Measures implemented to locally reduce UHI effects should be finely targeted to avoid exacerbating their relative higher exposure. This precaution is crucial given the regressive impacts, both in terms of initial exposure and income, observed in pollution mitigation policies (Champalaune 2020),[26] or in urban greening policies.[27]

Even if mitigation policies are spatially targeted to avoid short-term regressive impacts, they may have medium-term regressive effects due to spatial sorting. Indeed, improvements in local amenities can trigger gentrification, displacing incumbent households due to higher rents, thereby perpetuating their exposure in new locations. Le Thi et al. 2024 observes a similar pattern in the context of air pollution, where spatial sorting within urban areas perpetuates inequalities as affluent individuals move to less polluted municipalities.

[25] Estrada et al. 2017 present cost-benefit analyses of UHI mitigation options. Akbari and Taha 1992 provide simulations of the impact of trees and white surfaces on residential heating and cooling energy use in Toronto. Dagorn and Durand 2023 offer an online simulation in France *"Diminuez la température de votre rue"* (at the very bottom of the press article).

[26] Suarez Castillo et al. 2024 also show that exposure to air pollution is higher among children of low-income and high-income households. See also Colmer et al. 2024 for a thorough analysis of racial disparities in pollution exposure in the United States over the past three decades.

[27] Liotta et al. 2020 develop a criterion of well-being, including health, education, insecurity, and social relations, to prioritise areas where urban greening would have the greatest impact on well-being inequalities. In the case of the Paris metropolitan area, they show that the city of Paris and the inner suburbs would be targeted when considering income inequality in access to green spaces only. When inequalities in multidimensional well-being (health, education, insecurity, and social relations) are taken into account, the northern inner suburbs and some outer suburbs become a higher priority.

4 Vulnerable households facing UHI

In this section we explore the exposure of vulnerable households to UHI. First, we propose a definition of vulnerable households. We show that they are slightly more exposed to UHI and we underline the preponderance of income criterion in this increased exposure. Second, we measure their resources to mitigate or cope with UHI effects.

4.1 Vulnerability and exposure to UHI: the preponderance of income criterion

In this section, we propose a definition of vulnerable households as those below the poverty line, that is whose income is below 60% of the median income, and with at least one member over 65 or under 10.[28] Indeed, the elderly and young children, as well as low-income households,[29] all present a more fragile state of health than the population as a whole and are especially at risk regarding UHI.

In all cities, vulnerable households are slightly more exposed to UHI. This difference in UHI exposure is mainly driven by the income criterion and is higher when considering income alone. Indeed, we measure the UHI exposure, across cities, for vulnerable and non-vulnerable households (Figure 8) by considering only the income criterion in Panel (a), the age criterion in Panel (b) and the above definition combining the two criteria in Panel (c). We find that households below the poverty line are more exposed to UHI, but it is the opposite, albeit to a lesser extent in terms of magnitude, when considering households vulnerable only in terms of age. Hence, when combining the two criteria, we find that vulnerable households both in terms of income and age are slightly more exposed in all cities but Paris, with lower difference than when considering vulnerability in terms of income only. All differences are statistically significant (Table 8 in Appendix A.9).

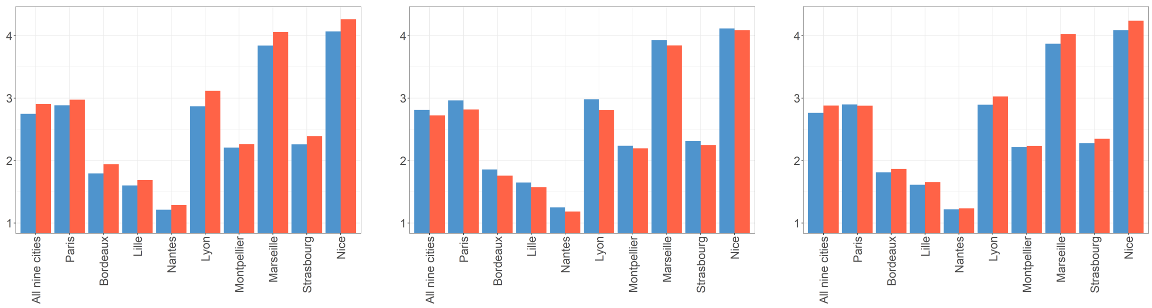
As we measure UHI exposure using simulated outside temperatures two meters above the ground (Section 2), we do not capture temperature heterogeneity within tiles, across buildings, and even within residential buildings due to factors such as dwelling orientation, insulation, and floor level. For instance, top-floor flats in multi-dwelling buildings are particularly susceptible to high indoor temperatures, whereas detached houses are less prone to overheating (Mavrogianni et al. 2012; Oikonomou et al. 2012). We find that vulnerable households are not necessarily the most exposed of their multi-dwelling buildings. Indeed, in all cities, vulnerable households are much more likely to live in a flat than non-vulnerable households, the differences in the share households living in a flat between vulnerable and non-vulnerable range from 7 to 24 % points across cities (Figure 9, Panel (a)). However, conditional on living in a flat, they are less likely to live on the

[28] By comparison, the definition of the U.S. Environmental Protection Agency socially vulnerable populations is based on age, income, education, race, and ethnicity criteria (EPA 2021). We use the data available here, i.e. age and income data, and the definition of poverty given by Insee, the French National Institute for Statistics and Economic Studies, which also prevails in most European countries.

[29] In 2017, in France, while 73% of people in the highest income quintile report being in good health, only 60% of people in the lowest income quintile do so (OECD 2017).

Figure 8: UHI exposure among vulnerable and non-vulnerable households: three definitions of vulnerable households

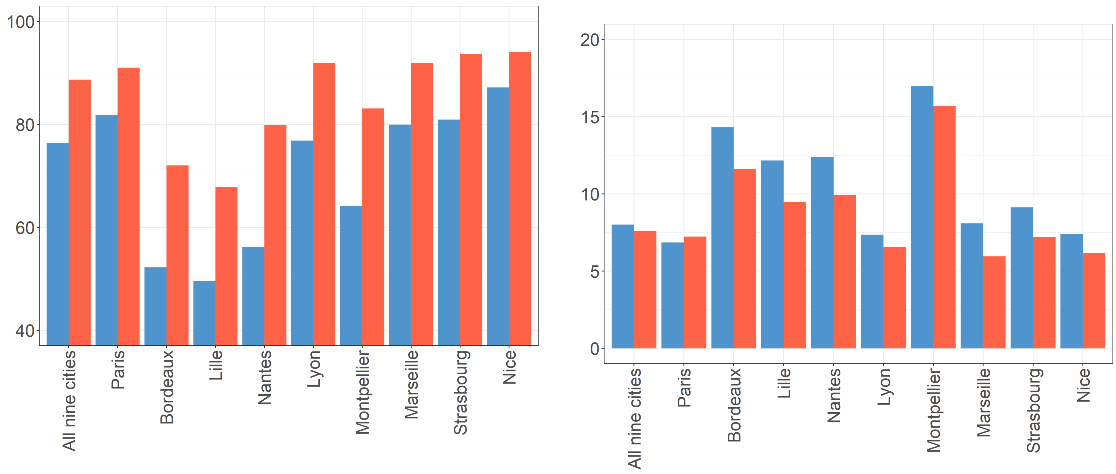
(a) Income criterion (b) Age criterion (c) Income and age criteria



Note: This figure compares, in Panels (a), (b), and (c), the UHI exposure of vulnerable (in red) and non-vulnerable households (in blue) across cities. The definition of vulnerable households in Panel (a) is based solely on income criteria: households whose income is below 60% of median income. Panel (b) uses only age criteria: households with at least one member aged less than 10 or more than 65 years old. Panel (c) combines both criteria.

Figure 9: Within-tile additional UHI risk factors: vulnerable vs. non-vulnerable households

(a) Flat (b) Highest floor



Note: This figure compares in Panel (a) the share (in %) of vulnerable (in red) and non-vulnerable households (in blue) that live in a flat, and in (b), conditional on living in a flat, the share living on the highest floor of their buildings.

top floor of their buildings, the difference with non-vulnerable households ranging from 0.4 to 2.7 % points (Figure 9, Panel (b)).

4.2 Vulnerable households have far less options facing UHI than non-vulnerable ones

As vulnerable households are slightly more exposed to UHI compared to non-vulnerable ones (Section 4.1), we now aim to measure their resources to mitigate or cope with UHI effects. There are several strategies households may employ to mitigate or cope with UHI effects. For many of them, the individual levels of action are strongly determined by income.

Improving home insulation. One household strategy is to improve the insulation of their home to adapt to heatwaves. However, there are significant obstacles, a major one being financial. Another is obtaining the necessary authorizations from one's landlord when living in private rental housing.[30] Indeed, renters in the private sector are slightly more likely to occupy an energy-inefficient dwelling than homeowners, with 20% compared to about 18% in 2021. However, renters in social housing are much less likely to live in an energy-inefficient dwelling, with less than 10% of them facing this issue (Le Saout et al. 2022). Thus, we compare, for each city, the shares of vulnerable and non-vulnerable households (a) living in a public housing, (b) renting a flat in the private sector, (c) being homeowners (Figure 11). We find that in all cities, vulnerable households are much more likely to live in a public housing, where the likelihood of living in a retrofitted dwelling is high, with differences with non-vulnerable households ranging from 13 to 47 % points. However, vulnerable households are also almost twice less likely to own their main residence. In Paris, Nice, and especially Marseille, vulnerable households are more likely than non-vulnerable households to rent a flat in the private sector.

Escaping the city. Another strategy to mitigate UHI effects is escaping when temperatures become excessively hot. This is more feasible for those who own a secondary dwelling outside the city and vulnerable households are three or four times less likely to do so (Figure 11, Panel (d)).

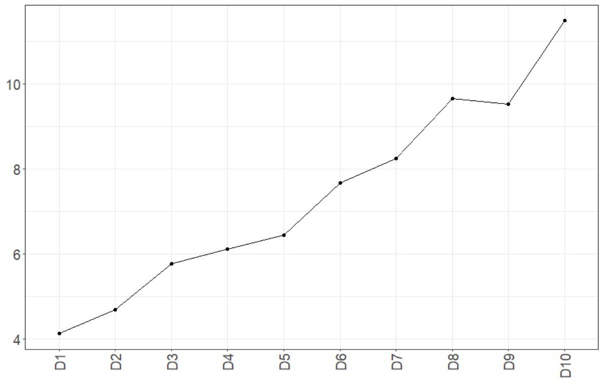
These differences are mainly due to the income criterion in our definition of vulnerable household as the share of homeowners and secondary dwelling owners increase with income, while the share of renters in the private sector or in social housing decrease with income (Figure 25 in Appendix A.8).

Air conditioning. For the others who stay at their homes with poor insulation, there are alternative methods to cope with extreme temperatures, such as purchasing air conditioning. However, high-income households are more likely to possess an air conditioning

[30] This is why the main thermal insulation subsidy schemes ("MaPrimeRenov", eco-PTZ) are aimed at homeowners (occupiers or lessors). However, as part of the energy-saving certificate scheme, energy suppliers can offer financial assistance (bonuses, vouchers, discounts, etc.) to individuals, whether tenants or homeowners, to partially or fully finance energy-saving work in their homes (Grislain-Letrémy and Mauroux 2024).

system (Figure 10). Similarly, in many countries, at low income levels air conditioning is rare but then starting at annual income of about $10,000 USD air conditioning increases sharply, before eventually leveling off at high income levels (Davis and Jarvis 2021).

Figure 10: Possession of an air conditioning system by income level



Note: This graph displays the share (in %) of households possessing an air conditioning system by income level. Source: French Housing Survey 2013

Access to medical facilities. Another option is seeking refuge in cool spaces provided by local authorities. Finally, a critical consideration given the potential adverse health effects of extreme temperatures on vulnerable households is their access to medical facilities. Vulnerable households live slightly closer to emergency facilities than non-vulnerable ones (Figure 12). This is due to the fact that, on average, vulnerable households reside slightly closer to the city center, in inhabiting areas that are slightly more exposed to UHI (Figure 3) but also closer to emergency facilities (Panel (b) of Figure 12).

4.3 Policy recommendations for actions at the household level

Simple measures such as reducing the use of air conditioning, which worsens heat stress outdoors, are efficient. The difficulty lies in the fact that air conditioning greatly reduces immediate heat stress. However, Viguie et al. 2020 provides a first quantified analysis of the efficiency of adaptation strategies (large scale urban greening, building insulation policy, generalized behavioral changes in air conditioning use) in reducing heat stress and thus future potential air conditioning need. They find that even ambitious strategies do not appear sufficient to totally replace AC and ensure thermal comfort, under a median climate change scenario. They can, however, reduce AC energy use by half during heat waves and compensate for the heat released to the outdoor environment.

At some point, when certain temperature thresholds are exceeded, public authorities may need not only to increase the number of cool islands to which households have access during the day, or increase the possibility of remote work to allow people to leave the city, but also to provide temporary places where households can sleep at lower temperatures at night, either outside cities or in adapted structures in city centers.[31]

[31] In Portland (Canada), for example, residents took refuge in air-conditioned gymnasiums set up by the authorities during the urban heat island of August 2021 (Berichel 2021).

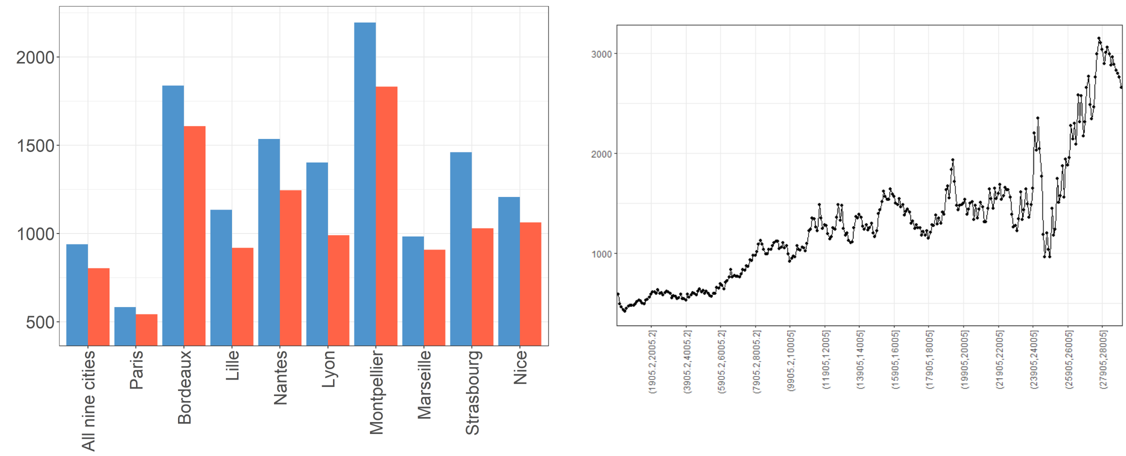
Figure 11: Share of households by occupation status and that possess a secondary dwelling: vulnerable vs. non-vulnerable households

Note: This figure compares, across cities, the shares (in %) of vulnerable (in red) and non-vulnerable households (in blue) in Panel (a) that live in a public housing, in (b) that are renters in the private sector, in (c) that are homeowners, and in (d) that own a secondary dwelling.

Figure 12: Distance to the nearest hospital

(a) Vulnerable vs non-vulnerable

(b) By distance to the city center



Note: This figure displays in Panel (a) the average distance of vulnerable and non-vulnerable to the nearest hospitals and in (b) the average distance to the nearest hospital across tiles, relative to the distance from the city center. Distances are measured in meters.

5 Conclusion

Climate change leads to an increase in the frequency, intensity, and duration of heatwaves. During heatwaves, the difference in temperature between cities and surrounding rural areas increases - and within cities -, especially at night, due to the urban heat island phenomenon. This phenomenon is caused by differences in urban form, architecture, materials used, vegetation, and the levels of human activity.

This paper investigates the relationship between income levels and exposure to UHI effects in France by constructing and matching finely localized data on temperature, vegetation, residential buildings, and socioeconomic characteristics of the inhabitants of nine major French cities. Our findings reveal that the relationship between UHI exposure and income mirrors the spatial sorting within cities. In cities where high- and low-income households reside closer to the city center than median-income households, UHI exposure follows a U-shaped curve. Conversely, in cities where the average distance to the city center increases with income, UHI exposure decreases with income. We show that vegetation, residential building density and height contribute to the unequal exposure to UHI based on income. The period of construction of residential buildings explains part of the difference between the two types of cities.

Vulnerable households, defined by age and income criteria, experience slightly higher UHI exposure than non-vulnerable households but have significantly fewer resources to mitigate UHI impacts. They are less likely to own their homes, making retrofitting challenging, and less likely to leave cities during heatwaves due to the lack of secondary dwellings. They also are less likely to be able to cool their dwellings as the possession of an air conditioning system increases with income.

This study is a first attempt to quantify unequal exposure to UHI in France and it opens avenues for future research. We assume that spatial sorting as of 2017 is not influenced by the differential effects of UHI within cities, believing that the location choices of affluent households depend on the amenities of living downtown or in the suburbs rather than UHI considerations. Future research could explore how intensified heatwaves might influence the endogenous location of households and potentially increase unequal exposure to UHI, as suggested by Hsiao 2024 on flood exposure inequality in Jakarta.

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Zulian, Grazia, Christina Corbane, Martino Pesaresi, Joachim Maes, Alessandro Stocchino, and Luc Feyen (2022). "Global long-term mapping of surface temperature shows intensified intra-city urban heat island extremes". *Global Environmental Change* 72.

A Appendix

A.1 Location of the nine cities on a map of France

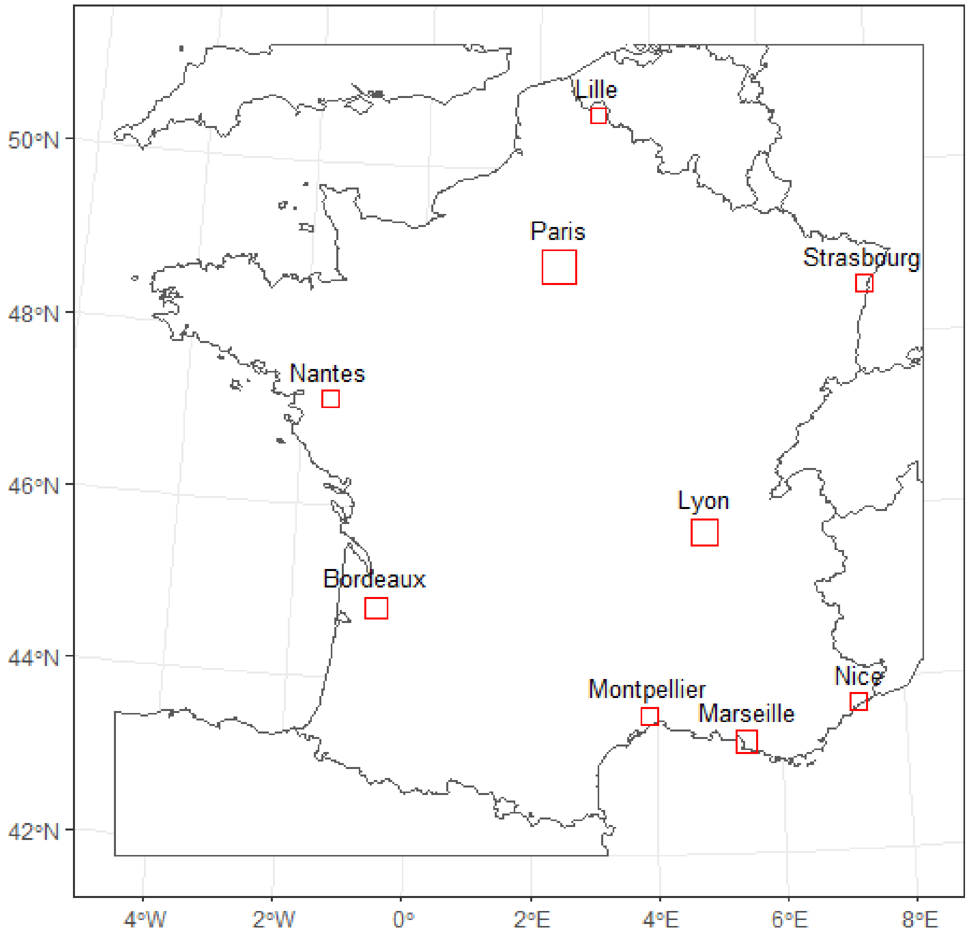


Figure 13: Location of the nine cities in France

A.2 Additional UHI indexes and summary statistics

We calculate three additional UHI indexes, for summer days and winter nights and days.

To do so, first, we calculate the daily minimum and maximum temperatures for each tile. We then compute the average of these maximums and minimums for tiles located in the countryside. For each tile, we calculate the difference between its maximum temperature (respectively minimum) and the average maximum (respectively minimum) in the countryside. The difference between minimums is called the UHI night index and the difference between maximums the UHI day index, as minimums typically occur at night and maximums during the day. Finally,HI night and day indexes during summer (May to August) and winter (December to February). In the body of the text, the UHI night index in summer is simply referred to as the UHI index.

We observe that the average UHI night index in summer is slightly higher than in winter, which is in turn higher than the UHI day index in winter, itself higher than the UHI day index in summer. This pattern holds true for both tiles and households (Table 6). It means that temperature differences with the countryside are, on average, magnified during summer nights.

Table 6: Summary statistics : UHI index at day and night, for summer and winter

UHI index (in °C difference)	Household database		Tile database	
	Mean	Sd	Mean	Sd
UHI night index (summer 2017)	2.8	1	2.1	0.99
UHI night index (winter 2017)	2.4	0.95	2	0.9
UHI day index (winter 2017)	1.3	0.69	0.82	0.64
UHI day index (summer 2017)	0.92	0.56	0.59	0.56
Number of observations	5,785,039		180,794	

A.3 Comparison between raw satellite image and pixel color analysis used in the vegetation index

(a) Satellite image from Sentinel

(b) Green pixels from satellite image

Figure 14: Comparison between raw satellite image and pixel color analysis used in the vegetation index - Western region of Paris

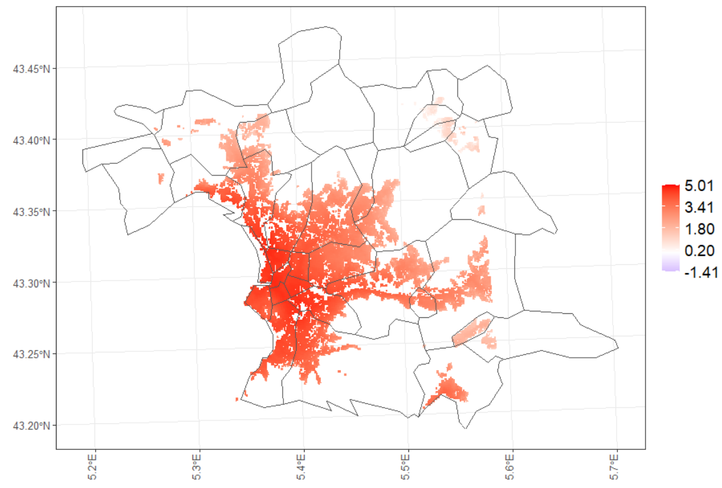
A.4 Description of the two databases built

Table 7: Description of the two databases built

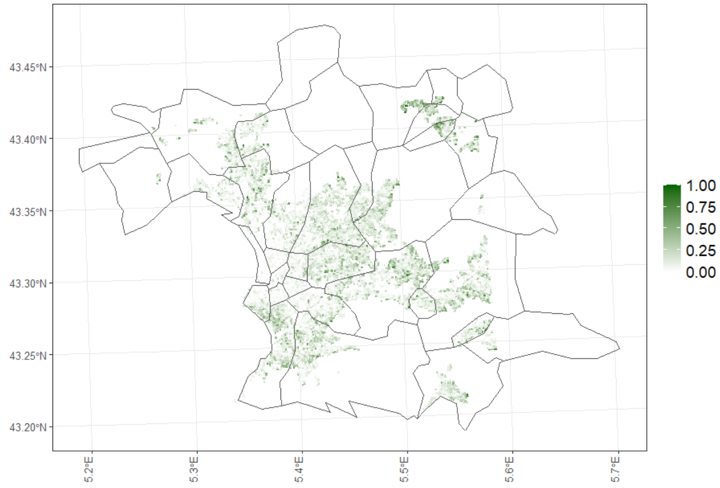
Variable	Household Database	Tile Database
UHI index	UHI index of the tile	
Vegetation index	Vegetation index of the tile	
Residential buildings period of construction	Period of construction of its building	Share of residential dwellings by period of construction
Residential buildings height	Maximum number of floors in the building of the dwelling	Average maximum number of floors in buildings of the tile
Residential buildings density	Sum of the surface areas of the residential dwellings located in the tile divided by the tile surface (10 000 m^2)	
Distance of the dwelling to the city center	Distance of dwelling to the city center	Average distance of dwellings in the tile to the city center
Distance of the dwelling to the nearest hospital	Distance of dwelling to the city center	Average distance of dwellings in the tile to the nearest hospital
Income	Its income	Average income
Age	Dummy indicating whether one member of the household is aged less than 10/more than 65	Share of households with one member aged less than 10/more than 65
Ownership status	Dummy indicating whether the household is a homeowner	Share of homeowners
Secondary dwelling	Dummy indicating whether the household owns a secondary dwelling	Share of households that own a secondary dwelling

A.5 Maps

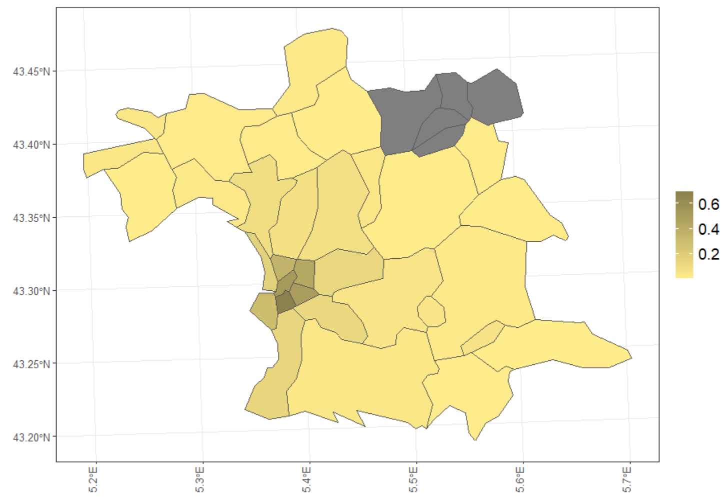
Figure 15: Marseille



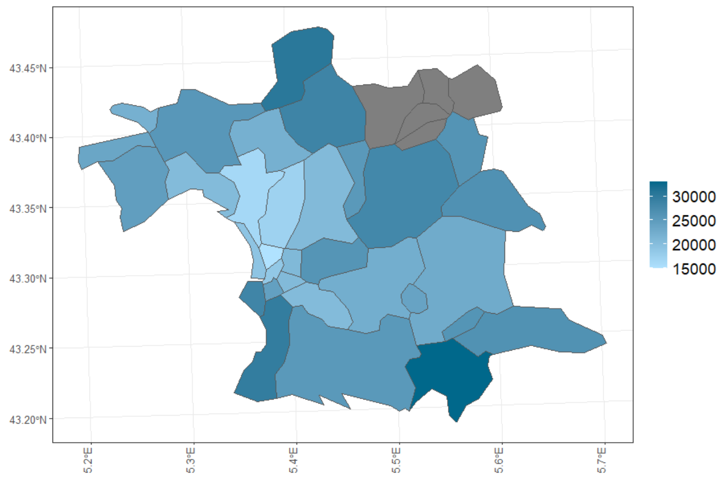
(a) UHI index (Δ degree Celsius)



(b) Vegetation (%)



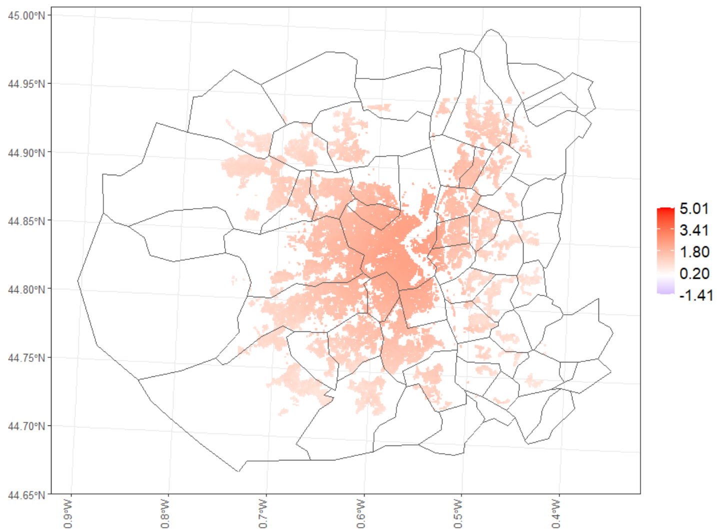
(c) Density



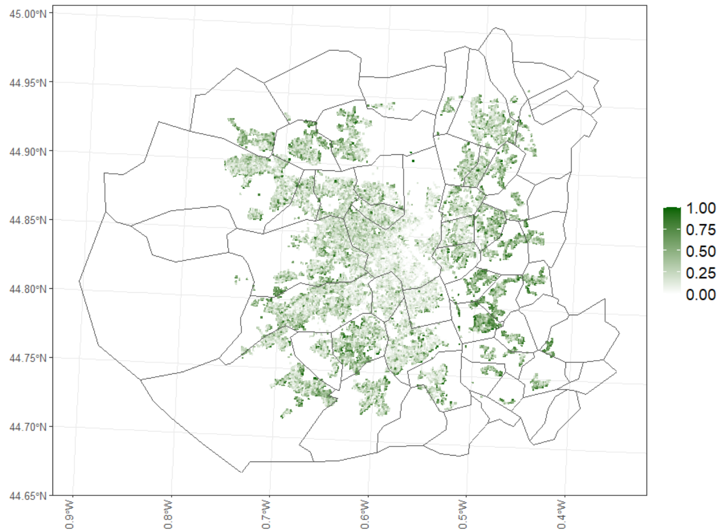
(d) Income (€ per CU)

Note: We present four maps of the city of Marseille. The grey borders represent all the city's municipalities. Maps (a) and (b) represent, at tile level, the UHI index in degrees Celsius difference with the surrounding countryside and the vegetation index in percentage of green pixels. Maps (c) and (d) represent, at municipal level, the density of residential buildings, calculated as the sum of the surface area of dwellings located in the tile divided by its surface area, and the household average annual income in € per consumption unit. Data dissemination rules to protect households confidentiality only allow us to present these two variables for municipalities with more than 5,000 inhabitants. This explains the grey municipalities in Maps (c) and (d). Note however that we do not have this type of restriction in our two databases. Conversely, households living in white tiles on Maps (a) and (b) are not covered by our databases.

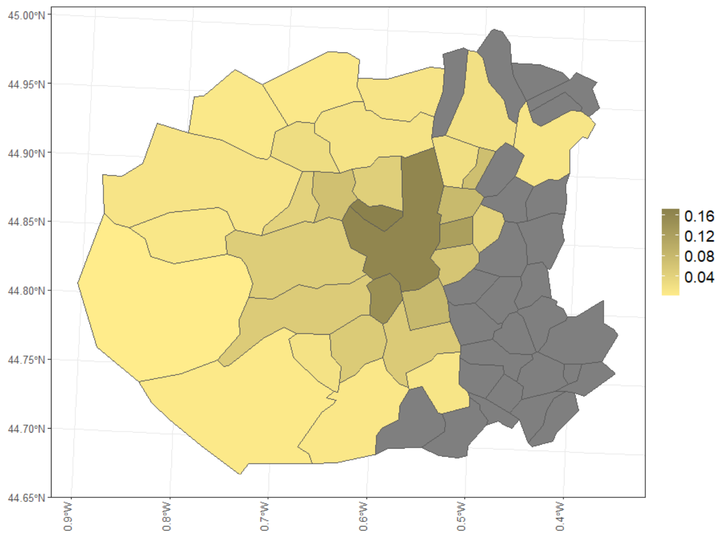
Figure 16: Bordeaux



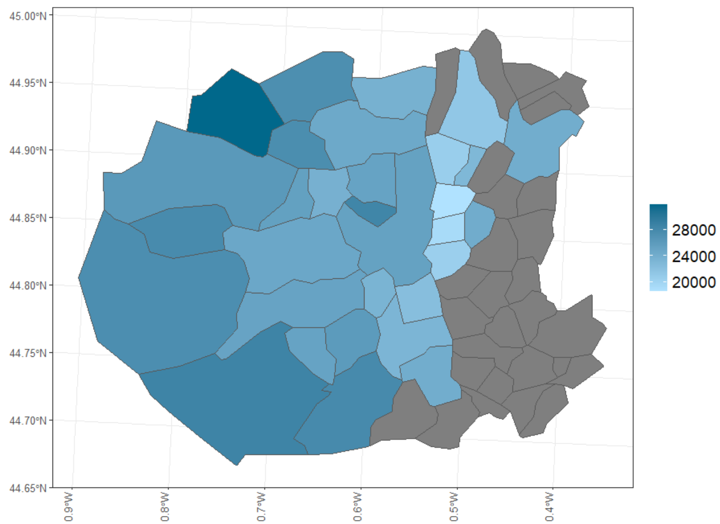
(a) UHI index (Δ degree Celsius)



(b) Vegetation (%)



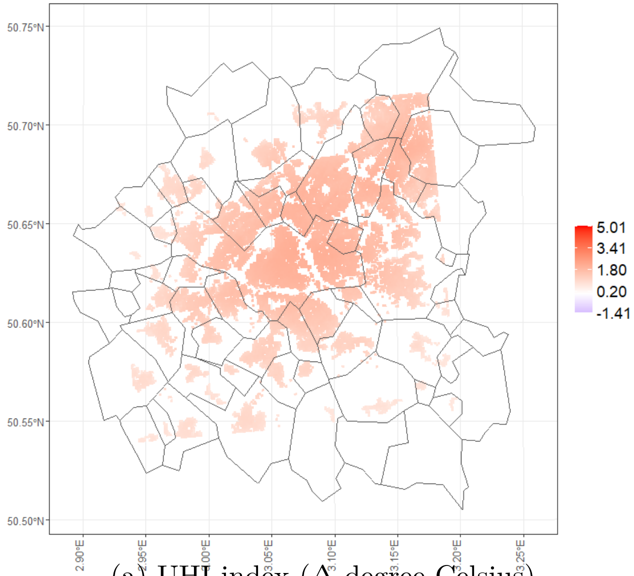
(c) Density



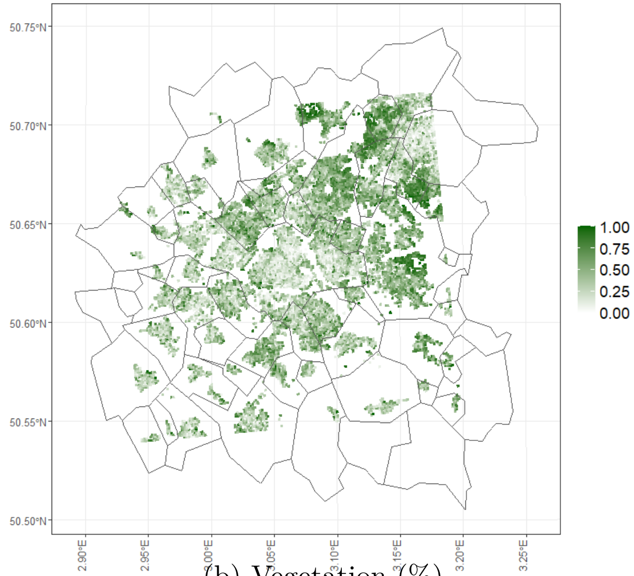
(d) Income (€ per CU)

Note: We present four maps of the city of Bordeaux. The grey borders represent all the city's municipalities. Maps (a) and (b) represent, at tile level, the UHI index in degrees Celsius difference with the surrounding countryside and the vegetation index in percentage of green pixels. Maps (c) and (d) represent, at municipal level, the density of residential buildings, calculated as the sum of the surface area of dwellings located in the tile divided by its surface area, and the household average annual income in € per consumption unit. Data dissemination rules to protect households confidentiality only allow us to present these two variables for municipalities with more than 5,000 inhabitants. This explains the grey municipalities in Maps (c) and (d). Note however that we do not have this type of restriction in our two databases. Conversely, households living in white tiles on Maps (a) and (b) are not covered by our databases.

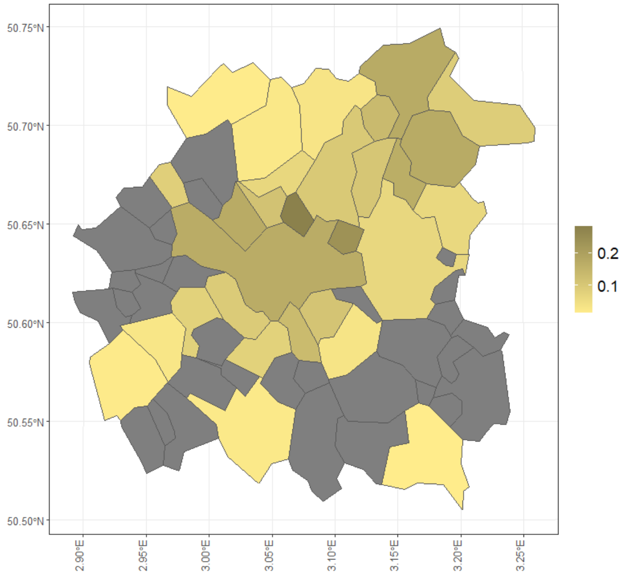
Figure 17: Lille



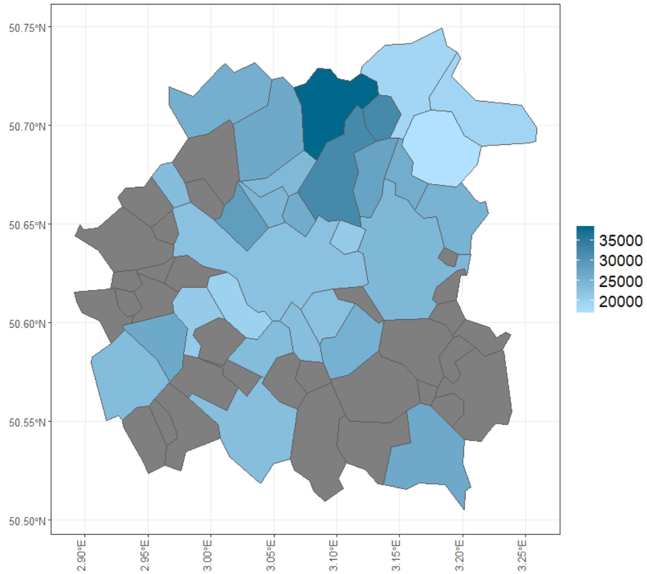
(a) UHI index (Δ degree Celsius)



(b) Vegetation (%)



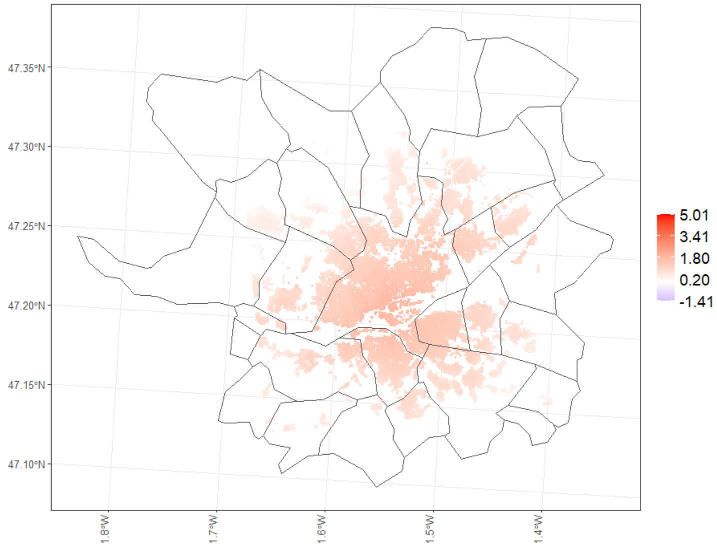
(c) Density



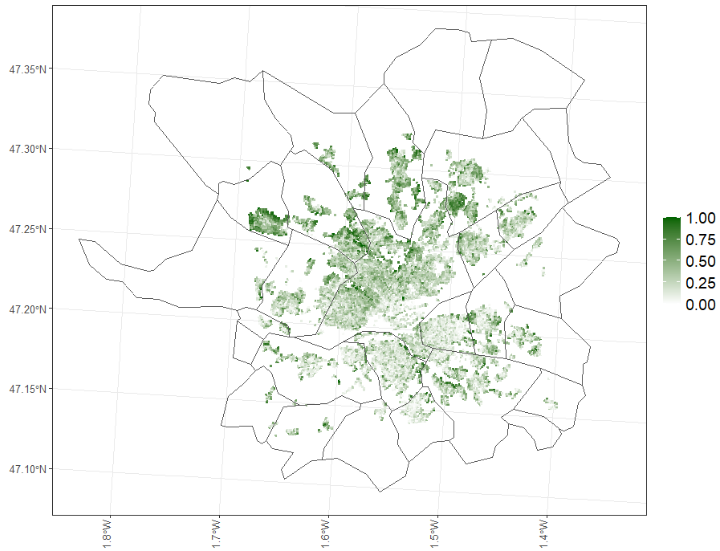
(d) Income (€ per CU)

Note: We present four maps of the city of Lille. The grey borders represent all the city's municipalities. Maps (a) and (b) represent, at tile level, the UHI index in degrees Celsius difference with the surrounding countryside and the vegetation index in percentage of green pixels. Maps (c) and (d) represent, at municipal level, the density of residential buildings, calculated as the sum of the surface area of dwellings located in the tile divided by its surface area, and the household average annual income in € per consumption unit. Data dissemination rules to protect households confidentiality only allow us to present these two variables for municipalities with more than 5,000 inhabitants. This explains the grey municipalities in Maps (c) and (d). Note however that we do not have this type of restriction in our two databases. Conversely, households living in white tiles on Maps (a) and (b) are not covered by our databases.

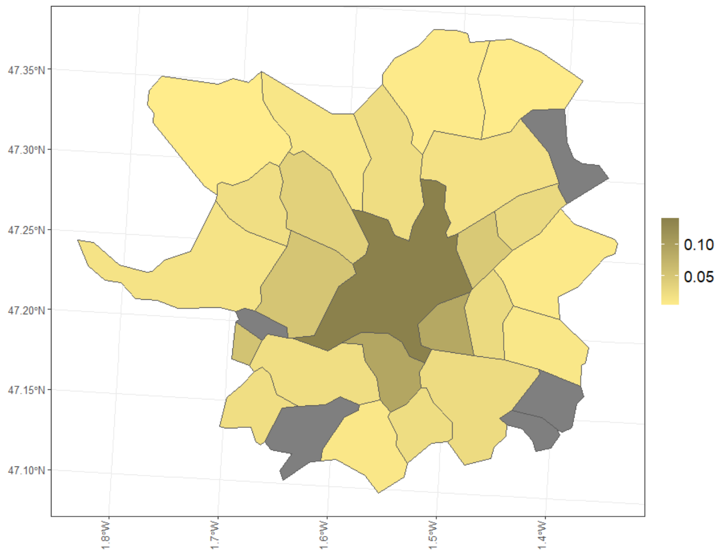
Figure 18: Nantes



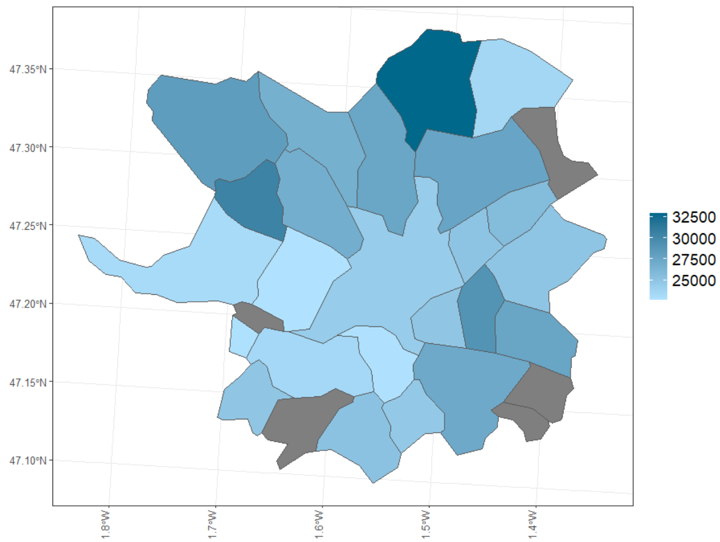
(a) UHI index (Δ degree Celsius)



(b) Vegetation (%)



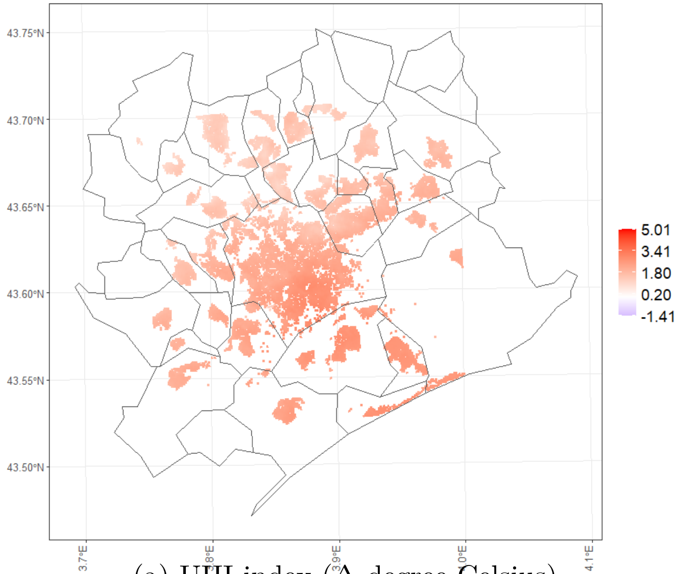
(c) Density



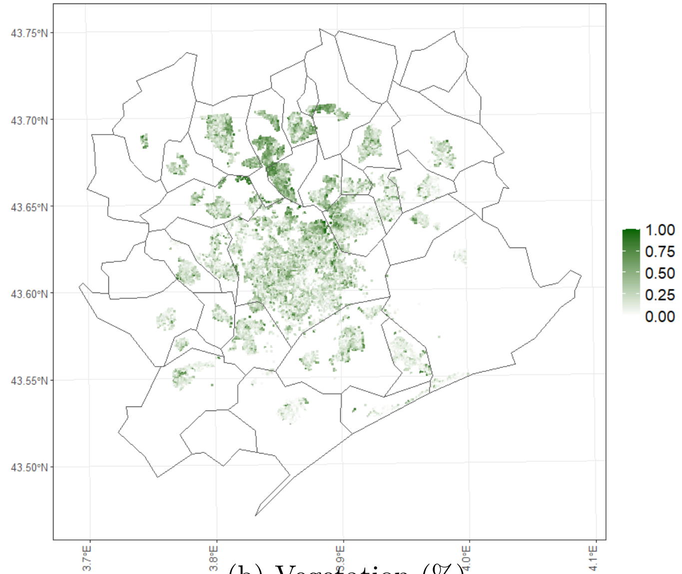
(d) Income (€ per CU)

Note: We present four maps of the city of Nantes. The grey borders represent all the city's municipalities. Maps (a) and (b) represent, at tile level, the UHI index in degrees Celsius difference with the surrounding countryside and the vegetation index in percentage of green pixels. Maps (c) and (d) represent, at municipal level, the density of residential buildings, calculated as the sum of the surface area of dwellings located in the tile divided by its surface area, and the household average annual income in € per consumption unit. Data dissemination rules to protect households confidentiality only allow us to present these two variables for municipalities with more than 5,000 inhabitants. This explains the grey municipalities in Maps (c) and (d). Note however that we do not have this type of restriction in our two databases. Conversely, households living in white tiles on Maps (a) and (b) are not covered by our databases.

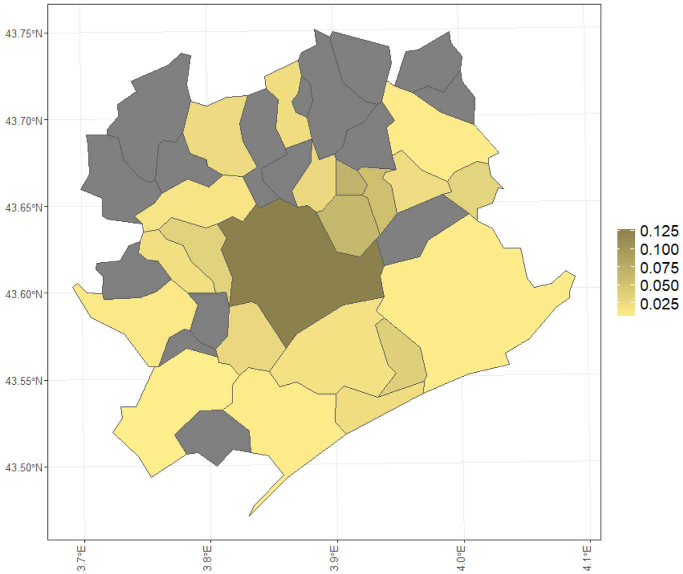
Figure 19: Montpellier



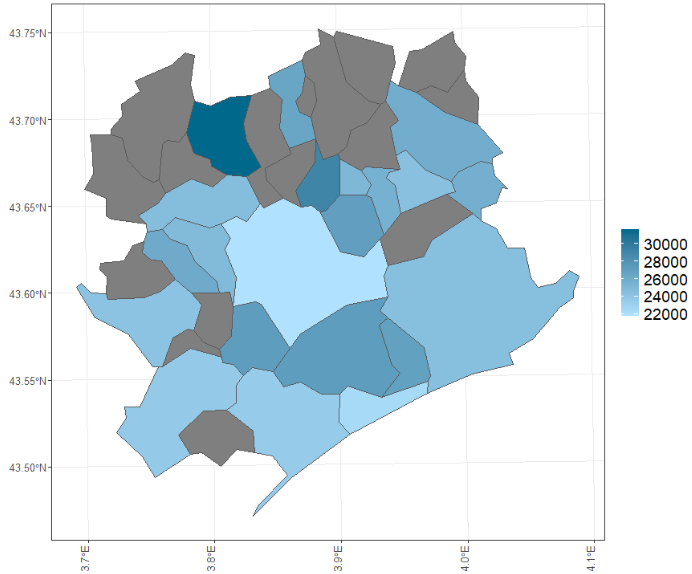
(a) UHI index (Δ degree Celsius)



(b) Vegetation (%)



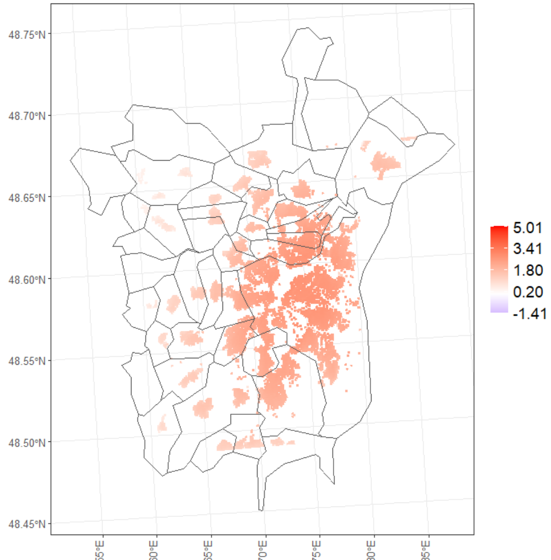
(c) Density



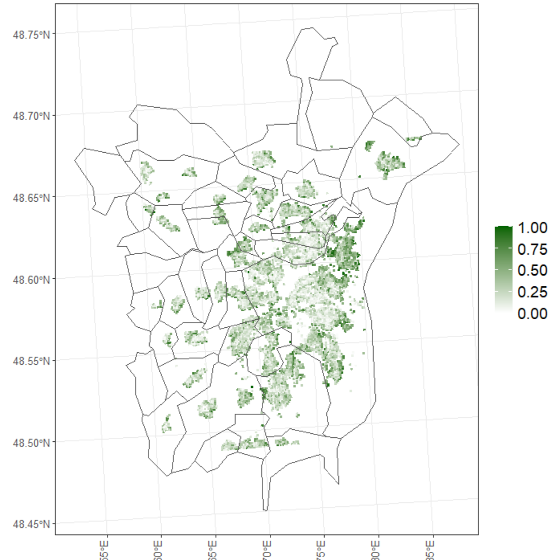
(d) Income (€ per CU)

Note: We present four maps of the city of Montpellier. The grey borders represent all the city's municipalities. Maps (a) and (b) represent, at tile level, the UHI index in degrees Celsius difference with the surrounding countryside and the vegetation index in percentage of green pixels. Maps (c) and (d) represent, at municipal level, the density of residential buildings, calculated as the sum of the surface area of dwellings located in the tile divided by its surface area, and the household average annual income in € per consumption unit. Data dissemination rules to protect households confidentiality only allow us to present these two variables for municipalities with more than 5,000 inhabitants. This explains the grey municipalities in Maps (c) and (d). Note however that we do not have this type of restriction in our two databases. Conversely, households living in white tiles on Maps (a) and (b) are not covered by our databases.

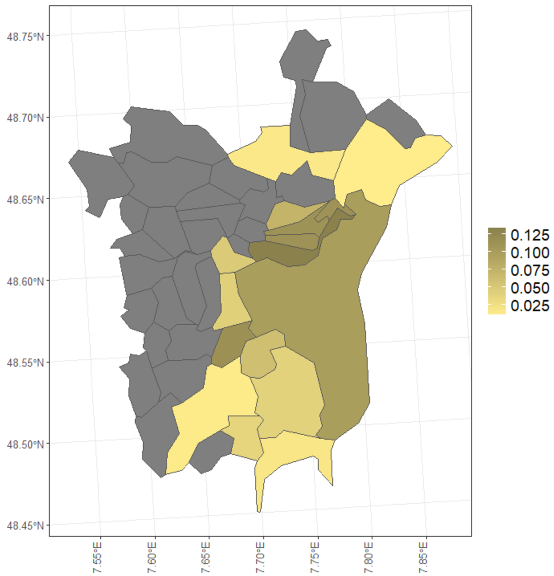
Figure 20: Strasbourg



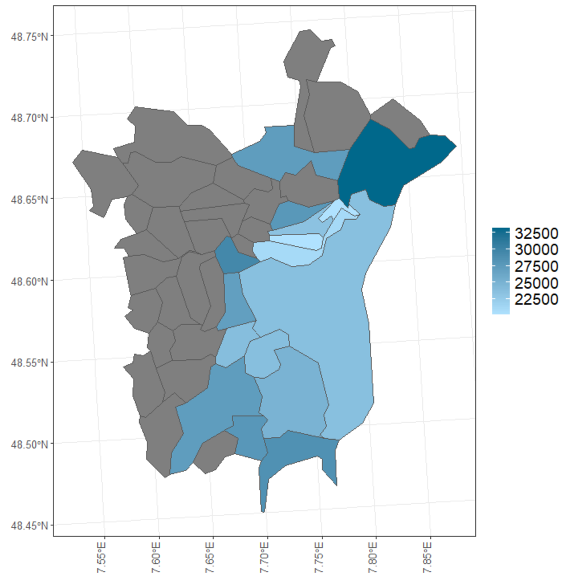
(a) UHI index (Δ degree Celsius)



(b) Vegetation (%)



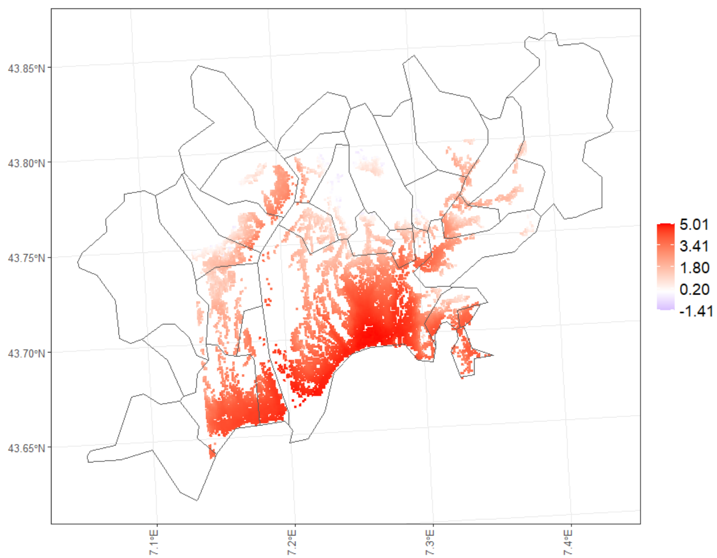
(c) Density



(d) Income (€ per CU)

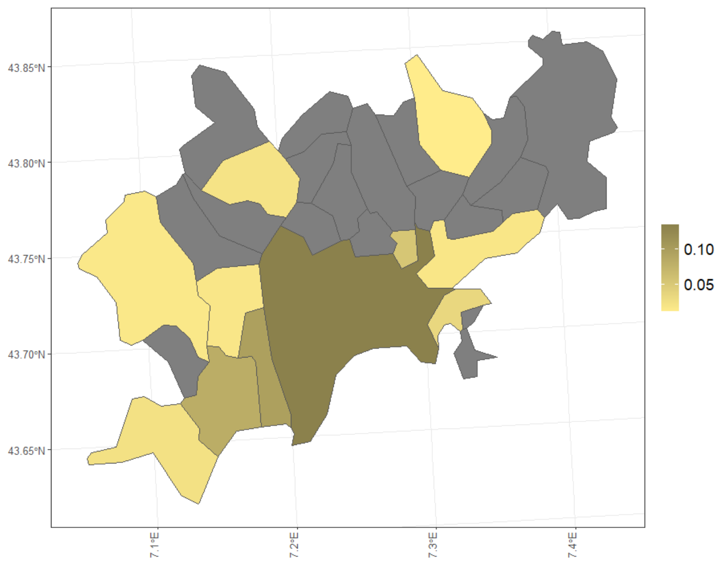
Note: We present four maps of the city of Strasbourg. The grey borders represent all the city's municipalities. Maps (a) and (b) represent, at tile level, the UHI index in degrees Celsius difference with the surrounding countryside and the vegetation index in percentage of green pixels. Maps (c) and (d) represent, at municipal level, the density of residential buildings, calculated as the sum of the surface area of dwellings located in the tile divided by its surface area, and the household average annual income in € per consumption unit. Data dissemination rules to protect households confidentiality only allow us to present these two variables for municipalities with more than 5,000 inhabitants. This explains the grey municipalities in Maps (c) and (d). Note however that we do not have this type of restriction in our two databases. Conversely, households living in white tiles on Maps (a) and (b) are not covered by our databases.

Figure 21: Nice

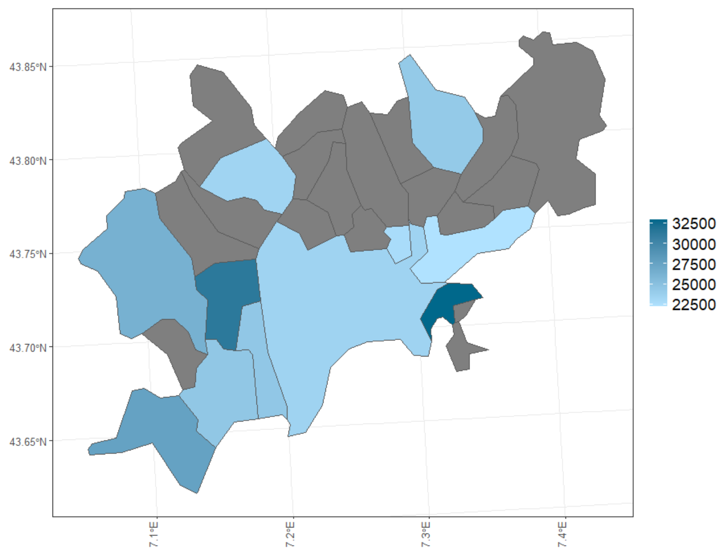


(a) UHI index (Δ degree Celsius)

(b) Vegetation (%)



(c) Density



(d) Income (€ per CU)

Note: We present four maps of the city of Nice. The grey borders represent all the city's municipalities. Maps (a) and (b) represent, at tile level, the UHI index in degrees Celsius difference with the surrounding countryside and the vegetation index in percentage of green pixels. Maps (c) and (d) represent, at municipal level, the density of residential buildings, calculated as the sum of the surface area of dwellings located in the tile divided by its surface area, and the household average annual income in € per consumption unit. Data dissemination rules to protect households confidentiality only allow us to present these two variables for municipalities with more than 5,000 inhabitants. This explains the grey municipalities in Maps (c) and (d). Note however that we do not have this type of restriction in our two databases. Conversely, households living in white tiles on Maps (a) and (b) are not covered by our databases.

A.6 Population distribution by national income decile in each city

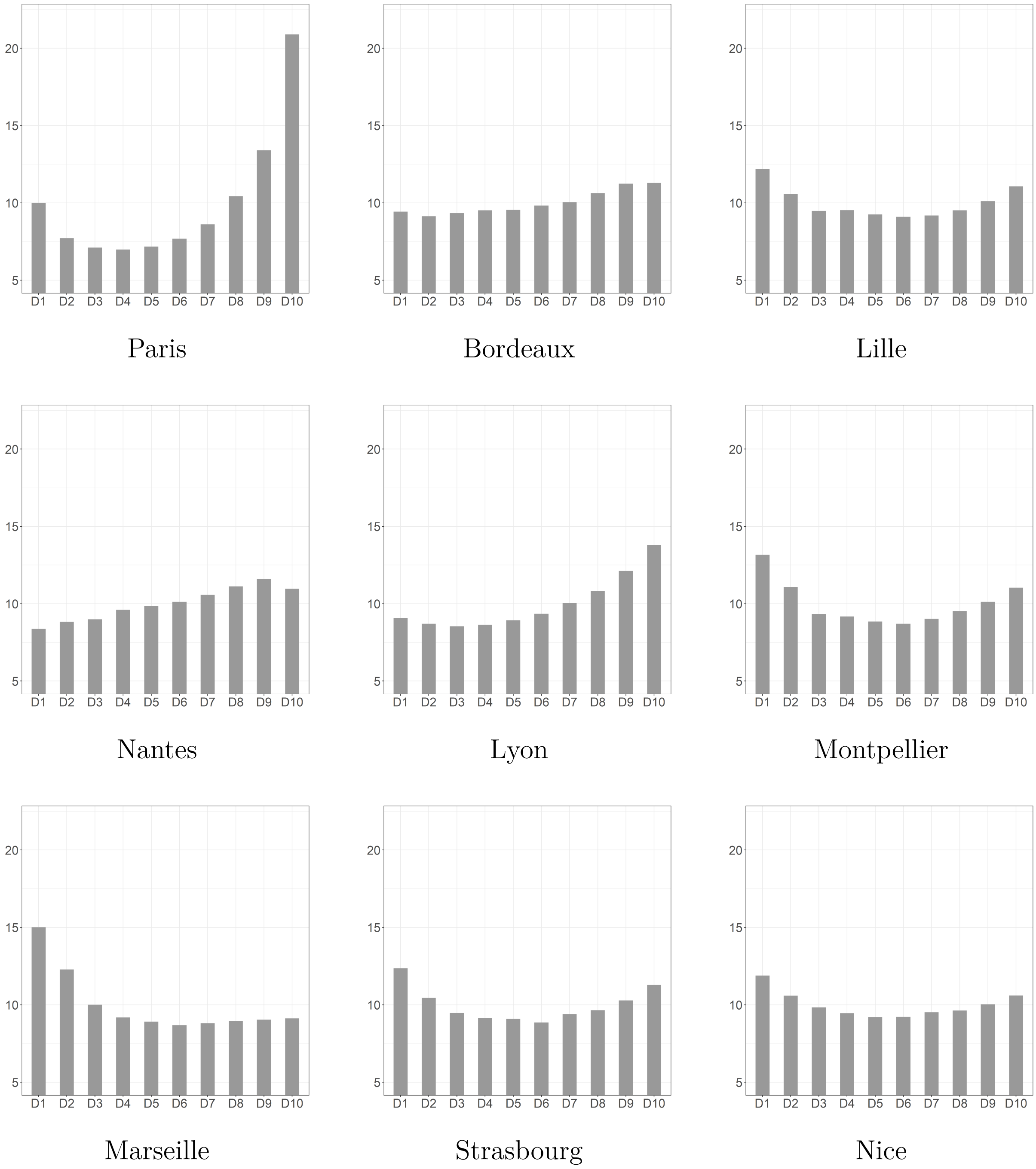
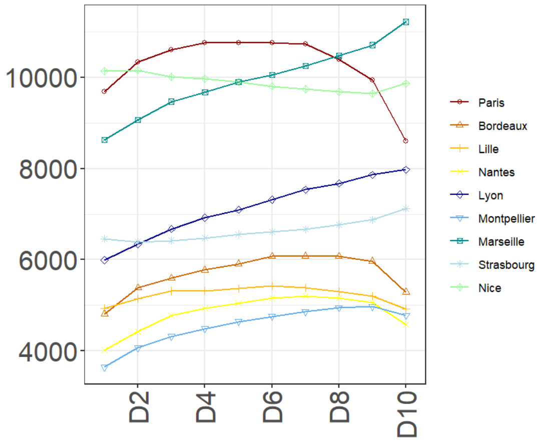


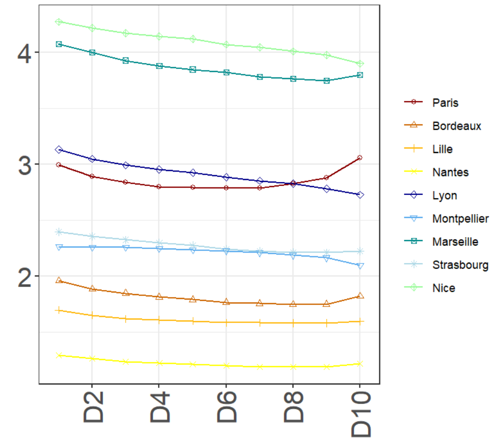
Figure 22: Population distribution by national income decile in each city (in %)

A.7 Key variables by national income decile and city

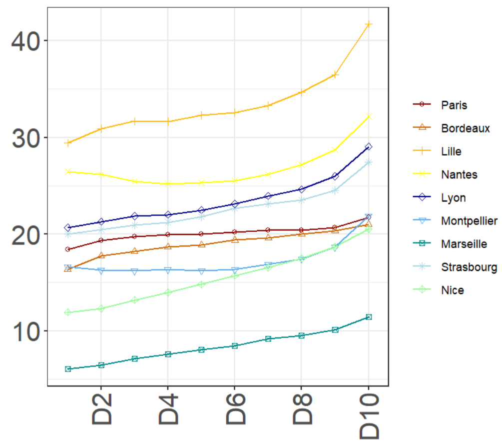
Figure 23: Distance to center, UHI index, vegetation and density by national income decile and city



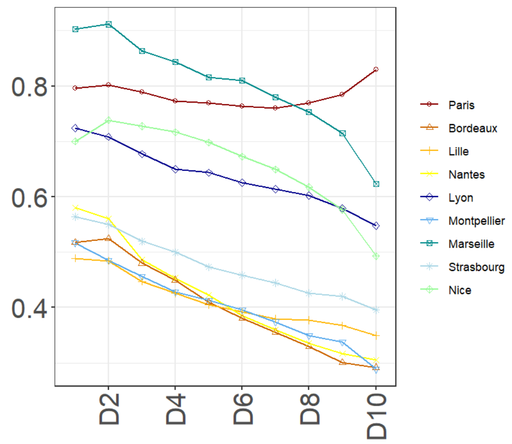
(a) Distance to center



(b) UHI index



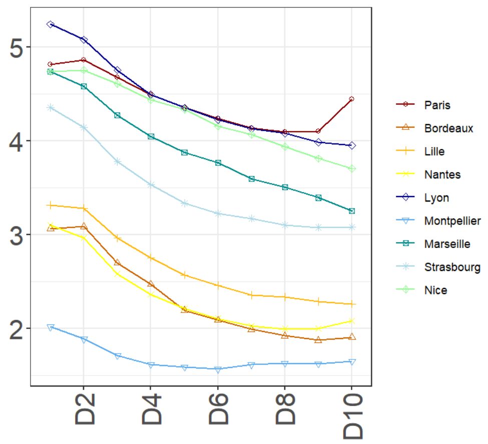
(c) Vegetation



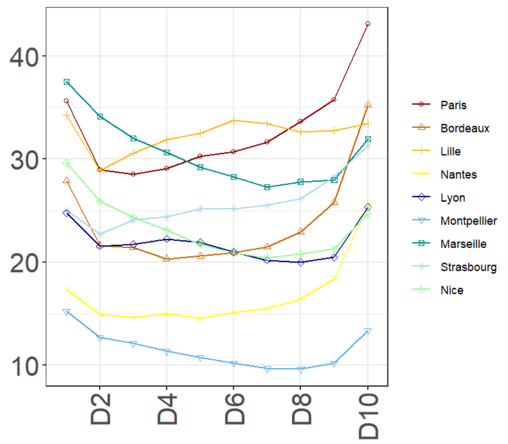
(d) Density

Note: This graph displays the mean distance to center (meters), UHI index (°C), vegetation index (%) and residential density (no unit) by national income decile and city.

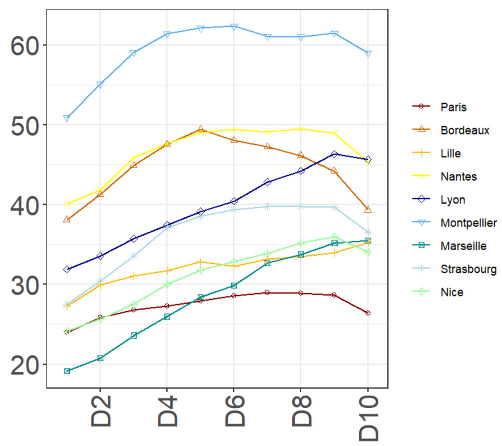
Figure 24: Building height and share of old and recent buildings by national income decile and city



(a) Height



(b) Share of old buildings



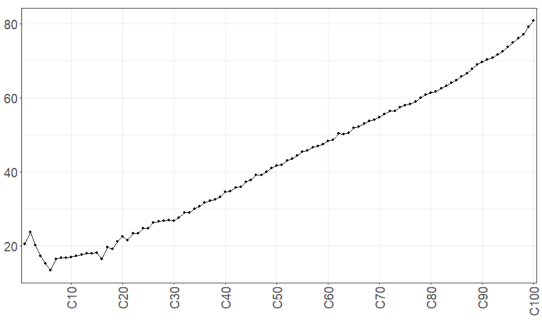
(c) Share of recent buildings

Note: This graph displays the mean residential building height (number of floors), and shares of old and recent buildings (%) by national income decile and city.

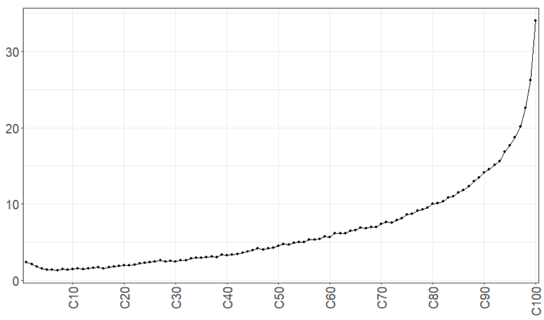
A.8 Shares of homeowners, secondary dwellings owners and renters by income

Figure 25: Shares of homeowners, secondary dwellings owners and renters by income

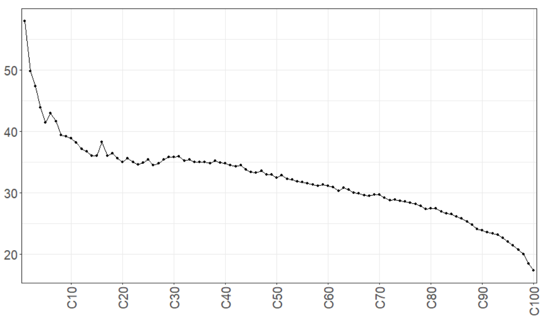
(a) Share of homeowners



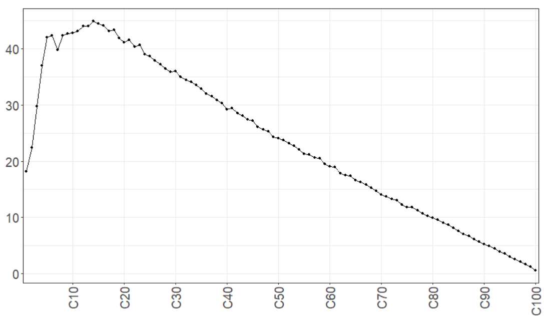
(b) Share of secondary dwelling owners



(c) Share of renters (private sector)



(d) Share of renters (social housing)



Note: This graph displays the shares (in %) in Panel (a) of homeowners, (b) of secondary dwelling owners, (c) of renters in the private sector, (d) of renters in social housing, all by national income centiles.

A.9 Comparing UHI exposure among vulnerable and non-vulnerable households

Table 8: UHI exposure among vulnerable and non-vulnerable households

	UHI index		
Vulnerability	No	Yes	Test
All nine cities			
Below poverty line	2.75	2.91	F= 16165.725***
Member under 10 or over 65	2.81	2.72	F= 10308.302***
Poor and member under 10 or over 65	2.76	2.88	F= 4022.247***
Paris			
Below poverty line	2.88	2.97	F= 3702.257***
Member under 10 or over 65	2.96	2.82	F= 21480.499***
Poor and member under 10 or over 65	2.9	2.88	F= 75.495***
Bordeaux			
Below poverty line	1.79	1.94	F= 4121.024***
Member under 10 or over 65	1.86	1.76	F= 3966.821***
Poor and member under 10 or over 65	1.81	1.87	F= 204.465***
Lille			
Below poverty line	1.6	1.69	F= 2905.017***
Member under 10 or over 65	1.65	1.57	F= 3532.096***
Poor and member under 10 or over 65	1.61	1.65	F= 272.824***
Nantes			
Below poverty line	1.21	1.29	F= 1281.294***
Member under 10 or over 65	1.25	1.18	F= 2203.248***
Poor and member under 10 or over 65	1.22	1.23	F= 16.211***
Lyon			
Below poverty line	2.87	3.12	F= 5235.025***
Member under 10 or over 65	2.98	2.81	F= 5762.519***
Poor and member under 10 or over 65	2.89	3.03	F= 690.336***
Montpellier			
Below poverty line	2.21	2.26	F= 396.573***
Member under 10 or over 65	2.24	2.2	F= 341.242***
Poor and member under 10 or over 65	2.22	2.24	F= 18.956***
Marseille			
Below poverty line	3.84	4.06	F= 5027.097***
Member under 10 or over 65	3.93	3.84	F= 1195.947***
Poor and member under 10 or over 65	3.87	4.03	F= 1339.219***
Strasbourg			
Below poverty line	2.26	2.39	F= 2282.963***
Member under 10 or over 65	2.31	2.25	F= 1039.727***
Poor and member under 10 or over 65	2.28	2.35	F= 303.749***
Nice			
Below poverty line	4.07	4.26	F= 1361.632***
Member under 10 or over 65	4.11	4.09	F= 45.972***
Poor and member under 10 or over 65	4.09	4.24	F= 430.477***

Note: F-test statistical significance markers: * p<0.1; ** p<0.05; *** p<0.01