

## ARTICLE OPEN



# Higher immigration and lower land take rates are driving a new densification wave in European cities

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Spatio-temporal density trends are considered key indicators of urban development. However, similar density trends may hide different drivers. This study investigates the density trends of 331 European cities between 2006 and 2018 and the underlying trends in residential area and population, broken down into natural change and net migration. The analysis captured a shift in the predominant trend from de-densification (2006–2012) to densification (2012–2018). Two main drivers determined the shift: (i) a more diffused growth of urban population, and (ii) a slowdown of land take for residential use after the global financial crisis of 2008. A clear acceleration in net migration rates, with immigration pushing population growth, occurred in most cities turning from de-densification to densification. Despite path dependencies and enduring differences across regions and city sizes, the distribution of these trends partly redesigned the traditional European East-West dichotomy into a novel center-periphery division.

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## INTRODUCTION

While urbanization proceeds in terms of both urban population growth<sup>1</sup> and urban land expansion<sup>2,3</sup>, density, generally defined as the ratio between population and occupied area, is a key indicator of its efficiency<sup>4</sup>. The physical expansion of cities threatens biodiversity<sup>5</sup>, causes the loss of agricultural land<sup>6,7</sup>, and alters climate at multiple scales<sup>8,9</sup>. Higher density means that less space is needed to accommodate the same population, hence more land is saved for other uses. Density changes in space and time, which have long been studied to describe different patterns and stages of urbanization<sup>10–12</sup>, have therefore assumed a normative meaning. While a growing scientific evidence points to a decrease in density in most urban areas worldwide<sup>2,4,13</sup>, policies at multiple levels encourage densification as a way to achieve a more sustainable urban development<sup>14–16</sup>.

Nevertheless, the same density trends can hide different urban development patterns. De-densification in growing cities, i.e. where population increases, can be considered an indicator of suburbanization or sprawl<sup>17</sup>, but in shrinking cities it may either simply indicate population loss, or conceal a decoupling between loss of population and expansion of residential areas<sup>18,19</sup>. On the other hand, although uncommon, large-scale demolitions can achieve densification even in the context of stable or shrinking population<sup>20</sup>. These examples suggest that similar density trends can be the result of different urban development trajectories, which produce different impacts on both human wellbeing and the urban environment. To correctly interpret density trends as a basis for policy-making, it is therefore imperative to consider the evolution of both their components: population change and land use change.

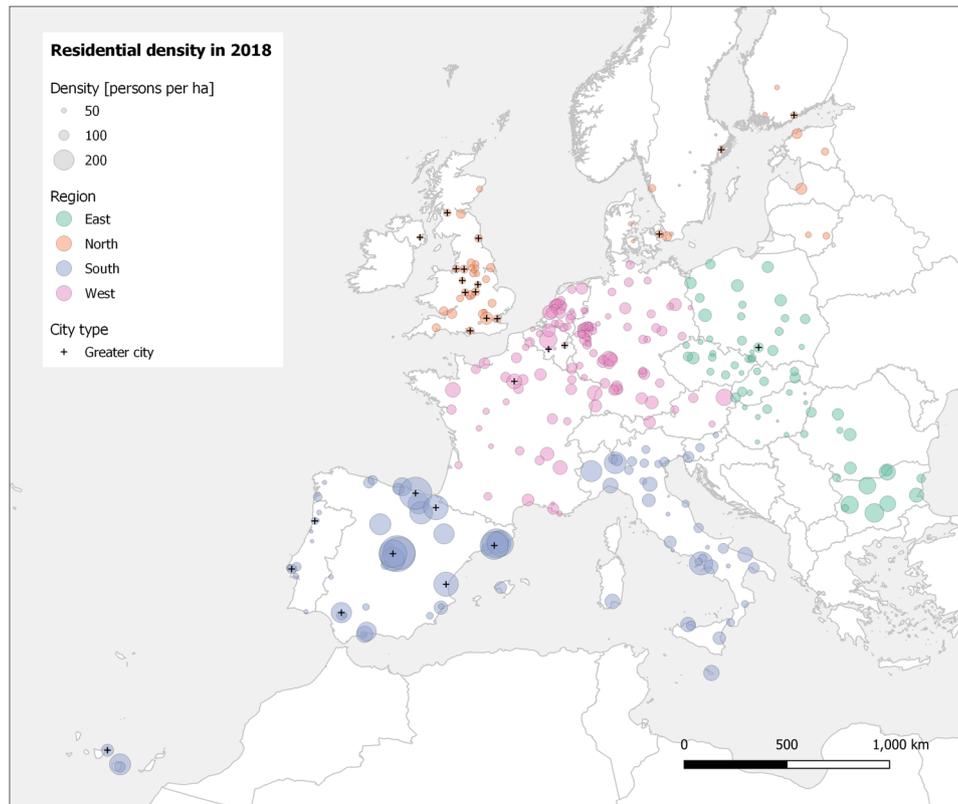
Concerning population change, both natural change and migration can play a role in density trends. Scholars have identified two main drivers of urbanization: the demographic transition, i.e. the shift from high to low death (and then birth) rates due to better living conditions<sup>21</sup>; and the mobility transition, i.e. the change from low to high levels of mobility thanks to

technological advancements, favoring movement from rural to urban areas<sup>22</sup>. While their roles and the causal relations between them are still debated<sup>23</sup>, the two transitions well explain the first stages of urban development<sup>24,25</sup>. Particularly, densification has been associated with the later phases of the demographic transition, where population growth is supported by a positive but slowing rate of natural change<sup>26</sup>.

However, the two transitions do not fully justify the suburbanization and inner-city reurbanization processes observed in some cities at later stages of development<sup>27,28</sup>. A 'second demographic transition'<sup>29</sup>, characterized by fertility rates significantly below replacement levels and disconnection between marriage and procreation, hence smaller households, aging, and different types of living arrangements, has been advanced as a possible explanation<sup>19,30,31</sup>. At the same time, new migration patterns, more complex and volatile than in the past, and less strictly linked to the labor market and the job opportunities offered by cities<sup>32</sup>, are gaining a prominent role as drivers of population growth<sup>33,34</sup>. Due to a combination of these factors, location choices are today—at least in western countries—more heterogeneous and affected by a broader variety of individual preferences compared to the past<sup>35</sup>, which also makes their impacts in terms of density more difficult to predict<sup>36,37</sup>. A further understanding of these trends, and especially of the possible different roles of natural change and migration in shaping the spatial development of cities, is key to support policies aimed at sustainable urban development<sup>38</sup>.

This study focuses on European cities. The variety of local geographic, climatic, historical, and socio-economic conditions, further amplified by a plurality of planning traditions and policies, makes Europe a privileged observatory to analyze the diversity of urban development<sup>16</sup>. Above this variety, the European Union ensures a certain level of coordination on key policy areas, including spatial development<sup>16</sup>. Of special relevance to the topic of density is the 'no net land take' strategy<sup>39</sup> promoted in 2011 by the European Commission with the aim to achieve no net loss of non-urban land by 2050. Among the tools to monitor the

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**Fig. 1 Residential density of European cities in 2018.** The 331 analyzed cities are classified according to the region. A mark indicates greater cities, i.e. urban agglomerations extending beyond the administrative boundaries of the respective core cities.

implementation of the strategy is the Urban Atlas<sup>40</sup>, a set of homogeneous land use land cover maps of European urban areas. Although limited to the years 2006, 2012, and 2018, the Urban Atlas allows tracking changes in urban land with unprecedented high resolution.

From 2006 to 2018, the construction of low-density residential areas has been the second most important driver of land take in the European Union<sup>41</sup>, in spite of the great recession caused by the global financial crisis of 2007–2008. During the same period, the European Union's population grew slightly, mostly due to the influx of immigrants and refugees increasingly compensating for an initially stable and then negative natural population change<sup>42</sup>. Internal migration between Member States, especially from East to West, has also increased since the enlargements of the Union in 2004 and 2007<sup>43</sup>. Some of these trends are expected to favor urban population growth, in accordance with the UN's predictions for the whole continent<sup>1</sup>. However, the impacts in terms of density are still unclear. Up until 2010, de-densification largely prevailed both in growing and shrinking urban areas<sup>20</sup>. The potential combined effect of demographic trends and policy drivers (such as the 'no net land take' strategy) in promoting a shift towards densification is still to be explored.

The aim of this study is to analyze the recent density trends of European cities, including the underlying trends in population and residential area, and to reveal if (and where) shifts from de-densification to densification occurred. We focus on 331 cities and compare their changes in residential density, population, and residential area between 2006, 2012 and 2018 by combining high-resolution land use land cover data from the Urban Atlas<sup>40</sup> with demographic data from Eurostat<sup>44</sup> and national statistical offices. We differentiate the contributions of natural population change (i.e., the difference between the number of births and the number of deaths) and net migration (i.e., the difference between the

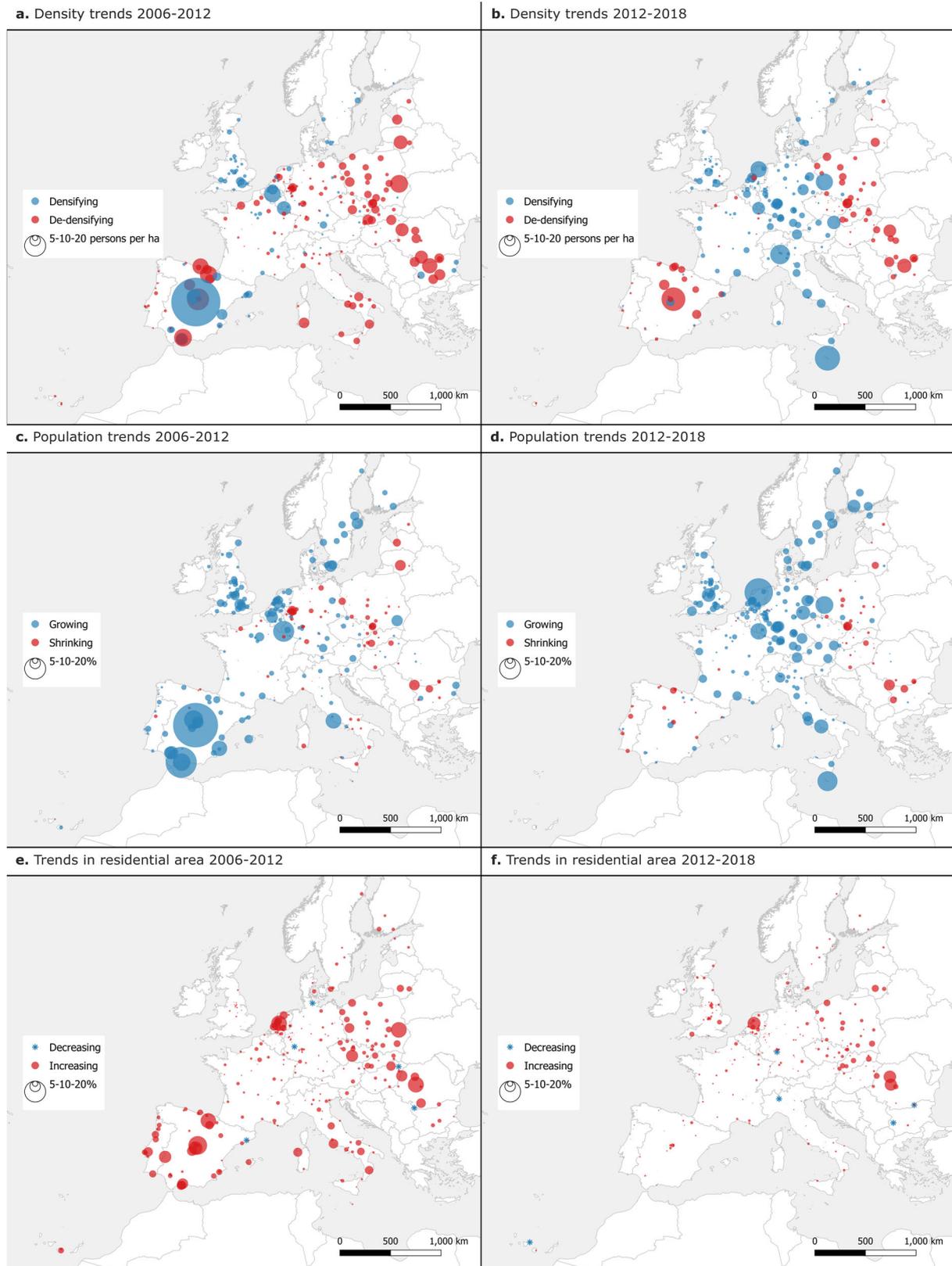
number of immigrants and the number of emigrants) to the total population change, to capture potentially different impacts on density trends. While the availability of data constraints the temporal coverage to the two periods 2006–2012 and 2012–2018, the wealth of existing studies on urban development in Europe provides a solid background to frame and support the interpretation of the results.

## RESULTS

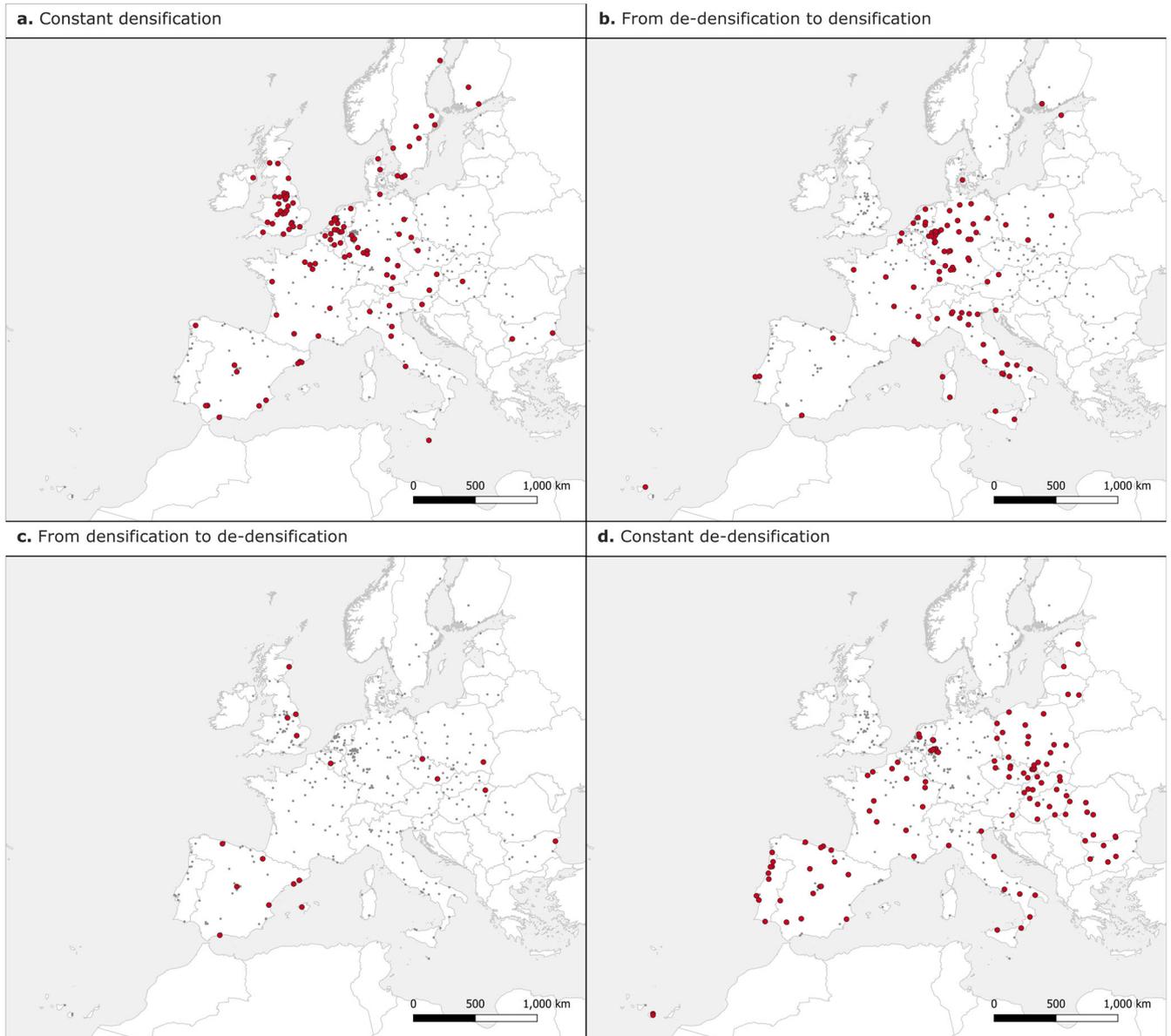
### Patterns of residential density across Europe and trends between 2006 and 2018

In 2018, i.e. the most recent year considered in the analysis, the residential density of the analyzed European cities ranged between around 20 persons/ha in Umeå (the most northern city in Sweden), to 356 persons/ha in Torrejón de Ardoz (close to Madrid, Spain). A clear North-South gradient is visible on the map (Fig. 1), with the densest cities in Spain and Italy, and the least dense in Sweden and Denmark. Such overall differences in residential density across regions existed already in 2006, and were mostly maintained throughout the analyzed period. Relevant differences between countries within the same region can also be observed (see also Supplementary Fig. 1), especially among southern and eastern cities, with Portugal and Hungary characterized by the lowest densities in the respective regional group. Size plays a role too, with large cities on average denser than small and medium-sized cities.

Between 2006 and 2012, de-densification was the most common trend, involving 60% ( $N = 201$ ) of the cities. However, the ratio reversed between 2012 and 2018 (Fig. 2a, b). Around one third of the sample ( $N = 114$ ) showed constant de-densification, and almost the same share ( $N = 112$ ) showed constant densification (Fig. 3). The remaining third of the cities showed a reversal in



**Fig. 2 Density trends and underlying trends in population and residential area.** The maps show the contribution of the changes in population (c, d) and residential area (e, f) to the changes in the residential density (a, b) of the analyzed cities. Panels (a), (c), and (e) refer to the period 2006–2012; panels (b), (d), and (f) to the period 2012–2018.



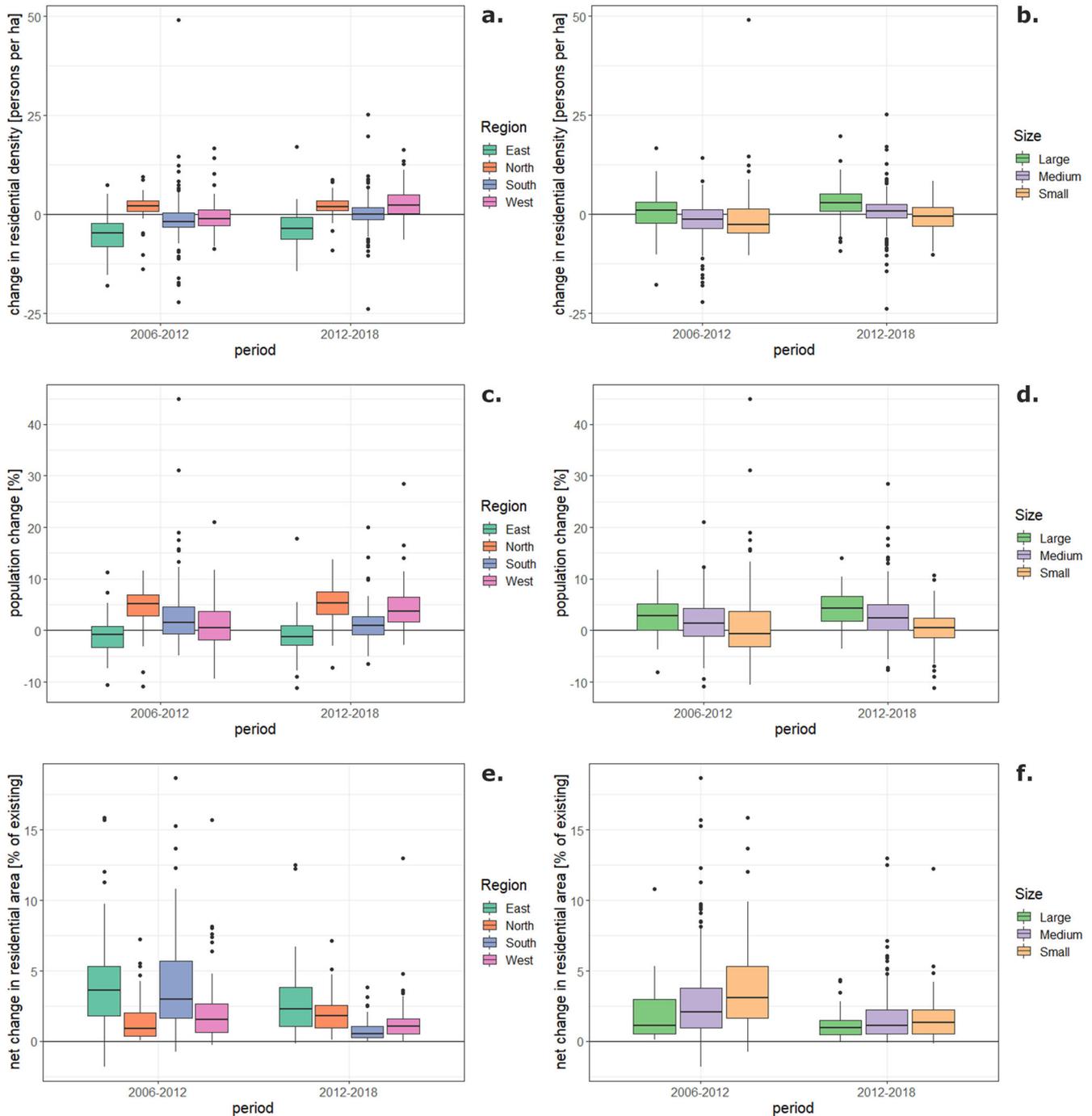
**Fig. 3 Density trajectories between 2006 and 2018.** Four main density trajectories are identified by comparing the density trends in 2006–2012 and 2012–2018: constant densification (**a**), from de-densification to densification (**b**), from densification to de-densification (**c**), and constant de-densification (**d**).

density trend between the first and the second period. Of these, the large majority ( $N = 87$ ) moved from de-densification to densification, while only 18 followed the opposite trajectory.

During the first period, residential density decreased in most eastern, southern, and western cities (Figs. 2a and 4a), especially in medium-sized and small cities (Fig. 4b). De-densification was particularly intense in the eastern countries and in southern Italy and Spain, but it also prevailed across German cities. Instead, densification was the most common trend in Belgium, the UK, and the Nordic countries. The pattern changed dramatically between 2012 and 2018 (Figs. 2b and 4a, b), when de-densification continued to prevail only in the most peripheral areas of Europe, both to the West, i.e. the Iberian Peninsula, and to the East, including the Baltic Republics. The majority of the other cities underwent densification processes, on average much more intense than in the first period. This intensity was particularly

high in cities in Italy, Germany, and the Netherlands, where density had decreased during the previous period.

Density trajectories were spatially clustered at the regional level, and most countries show a prevailing one (Fig. 3 and Supplementary Fig. 2). Constant densification prevailed in the northern region, including Sweden, Denmark, and the UK; and in large cities. In contrast, constant de-densification was the most common trajectory in the peripheral eastern and southern areas of Europe, and in small cities. A reversal from de-densification to densification characterized the majority of German and Italian cities in the sample. The shift from densification to de-densification was a cross-cutting phenomenon involving all regions -except the western region- and city sizes with almost the same intensity. The majority of cities moving from densification to de-densification were in Spain and in the UK.



**Fig. 4** Changes in residential density, population, and residential area of European cities grouped by region and size. The graphs show the distribution of the changes in residential density (a, b), population (c, d), and residential area (e, f) of the analyzed European cities grouped by region (a, c, e) and size (b, d, f) during the two periods 2006–2012 and 2012–2018.

#### Changes in population and residential area underlying the observed density trends

Considering the first component of density trends, i.e. population change, growth characterized most European cities in both periods (Fig. 2c, d). More than 60% ( $N = 204$ ) of the analyzed cities grew between 2006 and 2012, and the share increased to 75% ( $N = 247$ ) between 2012 and 2018. The spatial distribution of shrinking cities changed from prevailing in the eastern region but widespread also in most western and southern countries (Fig. 2c), to limited almost exclusively to the eastern countries and the Iberian Peninsula (Fig. 2d). In more than half of the eastern cities in

the sample, shrinkage was a continuous phenomenon, in some cases even accelerating in the second period (Fig. 4c). In contrast, almost all northern cities grew constantly, and in more than half of them, population growth accelerated in the second period. The most evident changes in population trends characterize Spain, with a relevant population growth in the first period followed by diffuse shrinkage or stagnation, and Germany and Italy in the opposite direction, with many cities shrinking between 2006 and 2012 and growing in the following period. Considering city size (Fig. 4d), growth prevailed across all classes, but it was more intense in large cities. The share of cities that grew constantly in

the two analyzed periods was higher in large cities than in medium-sized and small cities. Furthermore, an acceleration in population growth was more common in large than in medium-sized cities, and never observed in small cities.

This distribution of growing and shrinking cities is further detailed by decomposing population changes into natural change and net migration (Fig. 5). Migration was the prevailing trend (i.e., the one that determines the sign of population change) in the majority of the analyzed cities in both periods (207 cities between 2006 and 2012, and 231 between 2012 and 2018). This increasingly important role of migration was accompanied by an increase in the number of cases of diverging trends. Migration and natural change had the same direction in 60% of the cities ( $N = 198$ ) in the first period and in 53% ( $N = 177$ ) in the second period. Positive migration characterized only 42% of the cities ( $N = 138$ ) in the first period, but the figure grew to 56% ( $N = 186$ ) in the second period. At the same time, the share of cities characterized by a positive natural growth diminished respectively from 67 to 51% of the sample (from 222 to 169 cities). Supplementary Fig. 3 shows the frequency of detailed population trends in each group of cities classified according to region and size.

The second component of density trends, i.e. the change in residential area, shows a much less diverse picture (Fig. 2e, f). In almost all cities of the sample, residential area increased in both periods. Exceptions are only five cities between 2006 and 2012 (Vidin in Bulgaria, Kiel and Koblenz in Germany, Mollet del Vallès in the surroundings of Barcelona in Spain, and Nyíregyháza in Hungary) and just as many in the second period (Ruse and Pernik in Bulgaria, Darmstadt in Germany, Saronno in the periphery of Milan in Italy, and Santa Cruz de Tenerife in the Canary Islands, Spain). Between 2006 and 2012, the increase in residential area was particularly strong in eastern and southern cities (Fig. 4e). Between 2012 and 2018, the increase was overall lower, and the lowest in southern cities. Only eastern cities and cities in the Netherlands continued to show a relatively high increase in residential area. Many cities in the UK were characterized by a higher increase in the second period compared to the first one. While the size of the cities seemed to play a role in the first period, with a greater increase in residential area in small cities than in large cities, differences tended to disappear in the second period (Fig. 4f).

A pairwise correlation analysis between the analyzed variables helps to clarify their relationships (Fig. 6). In both periods, density change was significantly correlated to both change in population (positive correlation) and change in residential area (negative correlation). However, correlation with the former was stronger than with the latter, also due to the fact that densification always happened in growing cities: in the sample there is no evidence of cities shrinking and densifying at the same time. Considering the components of population change, a positive correlation of density change with both natural change and net migration was observed in both periods. Nevertheless, the correlation with natural change was lower, and decreased from the first (0.48) to the second period (0.30), while the opposite trend was registered for the (positive) correlation with net migration (from 0.71 to 0.78). At the same time, the change in residential area showed a significant but low correlation with the total change in population only in the first period (0.23), while it maintained a significant correlation with natural change in both periods (respectively 0.23 and 0.18), and a non-significant correlation with net migration (low significance only in the first period).

### Drivers of the different density trajectories

In our sample, we could never observe a case of densification in a shrinking city. This fact led to two consequences: (i) continuous shrinkage (i.e., population loss) always produced constant de-

densification, and (ii) a shift from growth to shrinkage (i.e., from positive to negative population change) in densifying cities always implied a parallel shift to de-densification. However, as de-densification also occurred in many growing cities, including cities that shifted from shrinkage to growth, changes from densification to de-densification (and vice-versa) cannot be attributed solely to an inversion in population trends.

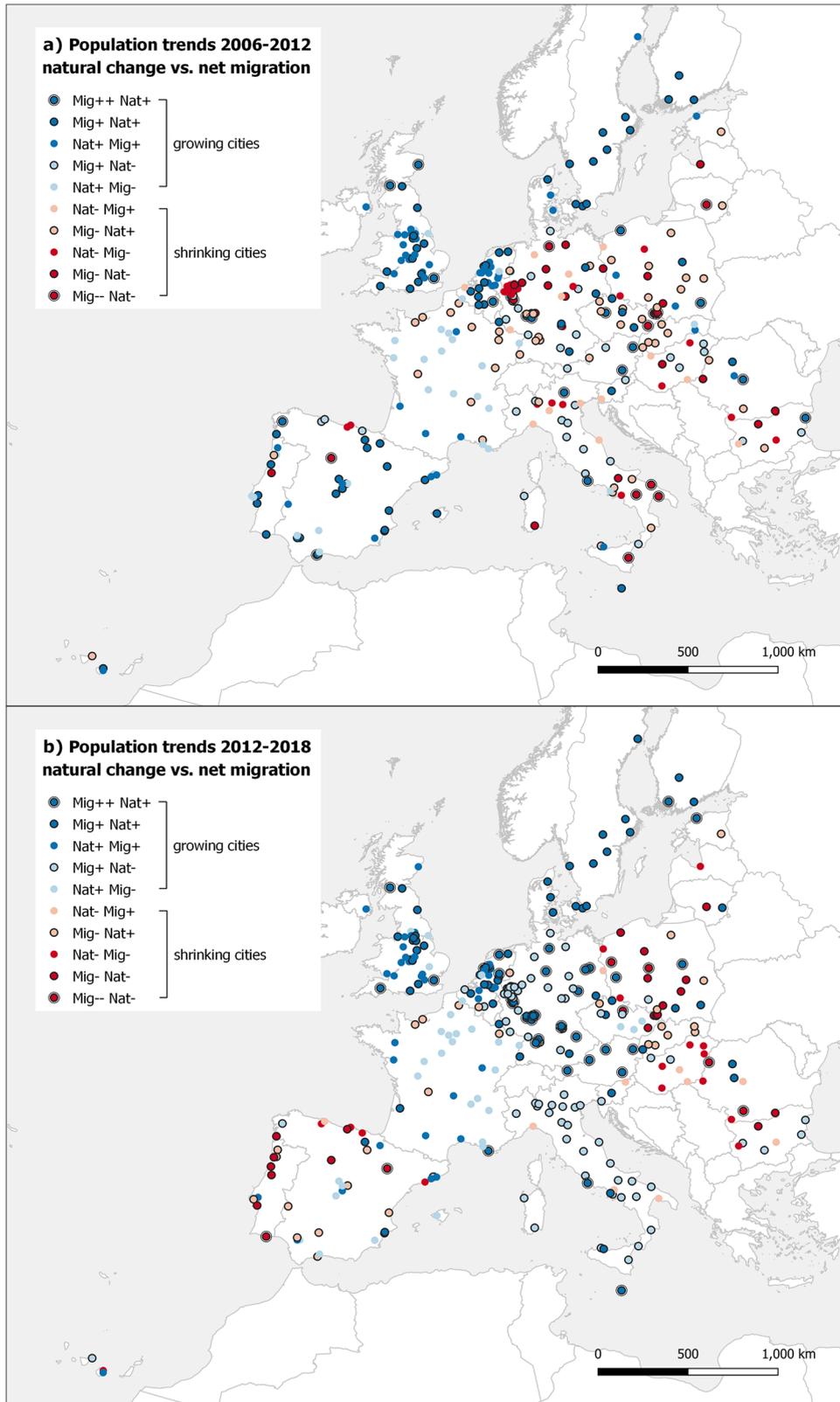
As shown in Fig. 7, density trajectories are linked to the variation in population change between the two periods. Constant densification was mostly observed in cities with small variations in population changes between the two periods (in Fig. 7, the distribution is skewed along the bisector indicating equal change). Shifts from de-densification to densification were frequently associated with an acceleration in population change, either from shrinkage to growth (second quadrant) or from slow to fast growth (points close to the positive vertical axis). In contrast, shifts from densification to de-densification were frequently linked to a slowdown in population growth rates, either from growth to shrinkage (fourth quadrant) or from faster to slower growth (points close to the positive horizontal axis). Finally, constant de-densification was a transversal phenomenon cross-cutting all combinations of demographic changes during the two periods. It characterized all cities shrinking in both periods and prevailed in cities shrinking in at least one of the two periods, but it was also found in thirteen cities characterized by a constant growth. However, similar to constant densification, constant de-densification was in most cases linked to small variations in population change.

The large variations in population change associated with reversals in density trends, especially from de-densification to densification, were more often pushed by migration than by natural change (Fig. 8 and Supplementary Fig. 4). What distinguished cities with a continuous de-densification trend (in red in the graphs) from cities that moved from de-densification to densification (in green) was often a shift from negative to positive migration, while natural change remained similar in the two periods, and negative in most cases. On the other hand, cities shifting from densification to de-densification (in orange) were characterized, on average and in both periods, by a natural change similar to that of cities with constant densification (in blue). What distinguished them was a slowdown in migration rates, often shifting from positive to negative. Overall, differences in net migration rates were the main component of population change (Fig. 8 and Supplementary Fig. 4) and can be considered the primary driver of the observed reversals in density trends.

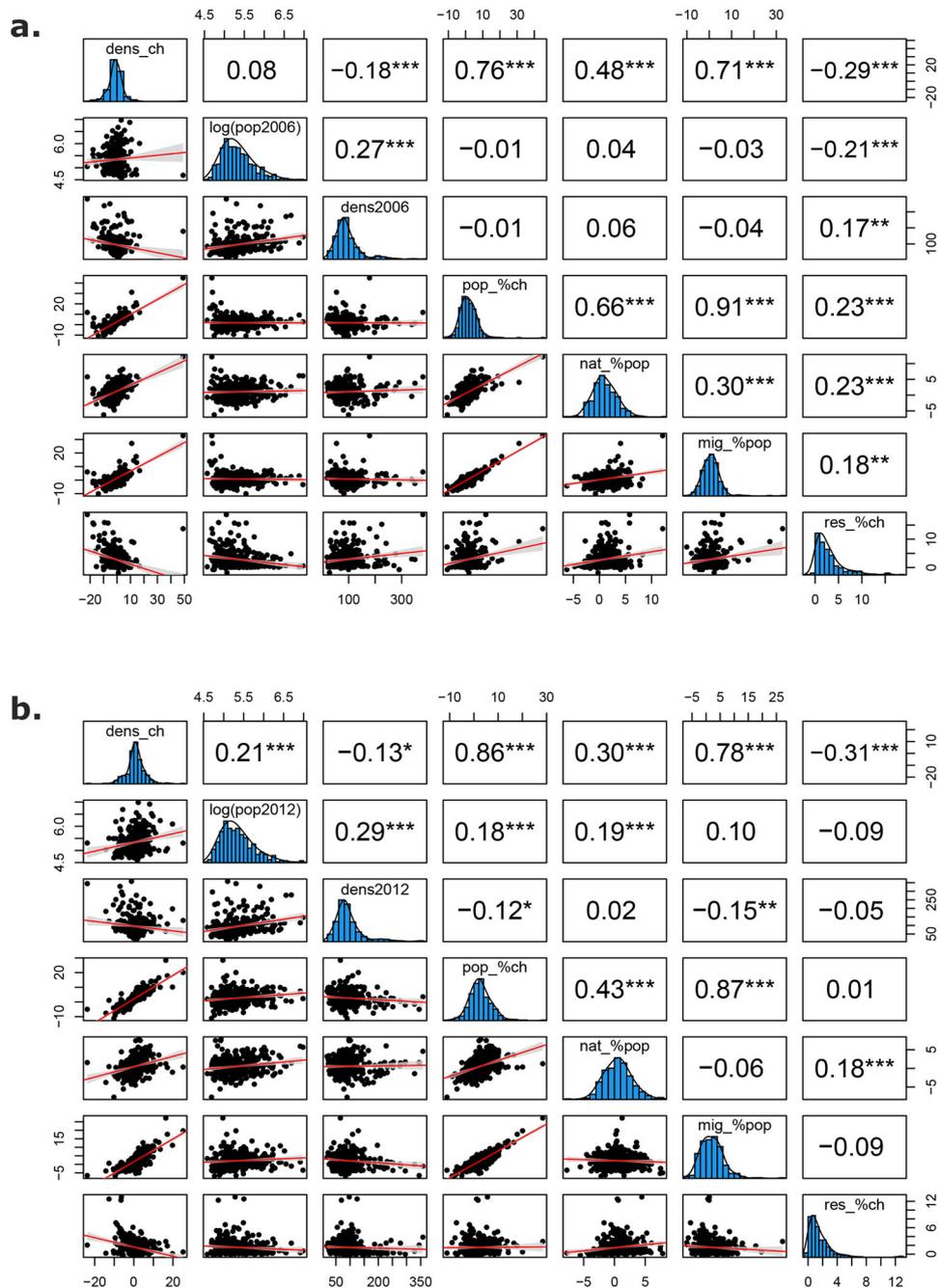
## DISCUSSION

The analysis captured a shift in the recent urban development of European cities from diffuse de-densification to prevailing densification. While between 2006 and 2012 residential density still declined in most European cities, the majority of them showed in the following 6 years an increase in density, with one-quarter of the sample turning from de-densification to densification. Two main trends determined this shift. The first one is a more diffused population growth, with shrinkage limited to more restricted geographical areas (eastern cities and the Iberian Peninsula). An inversion of population dynamics was observed in the majority of cities in Italy and Germany and in some cities in France and Czechia. The second trend is a sharp reduction in land take for residential use between the two periods, which was observed in more than two-thirds of the cities in the sample.

The results for the first period are coherent with several studies showing a continuous decline in density during the last decades, not only in Europe and in other 'land-rich developed countries' such as USA and Canada<sup>12,20</sup>, but also in fast developing economies such as India and China<sup>4,45</sup>. In this context, the predominant tendency of European cities to (re-)densify in the



**Fig. 5** Population trends in 2006–2012 and 2012–2018 broken down into natural change and net migration. Nat = natural change, Mig = net migration. Red dots correspond to shrinking cities, blue dots to growing cities (see Fig. 2 panels c and d). The trend cited first in the legend is the prevailing one (circles with a black outline indicate prevailing migration, circles without outline indicate prevailing natural change). The signs + and - in the legend indicate positive and negative change respectively; ++ and -- signal cases in which the contribution of net migration is at least 5 times greater than that of natural change. Light hues are used when the two trends are contrasting (i.e., one positive and the other one negative), dark hues that they are concordant (i.e., both positive or both negative). Panel (a) refers to the period 2006–2012, panel (b) refers to the period 2012–2018.

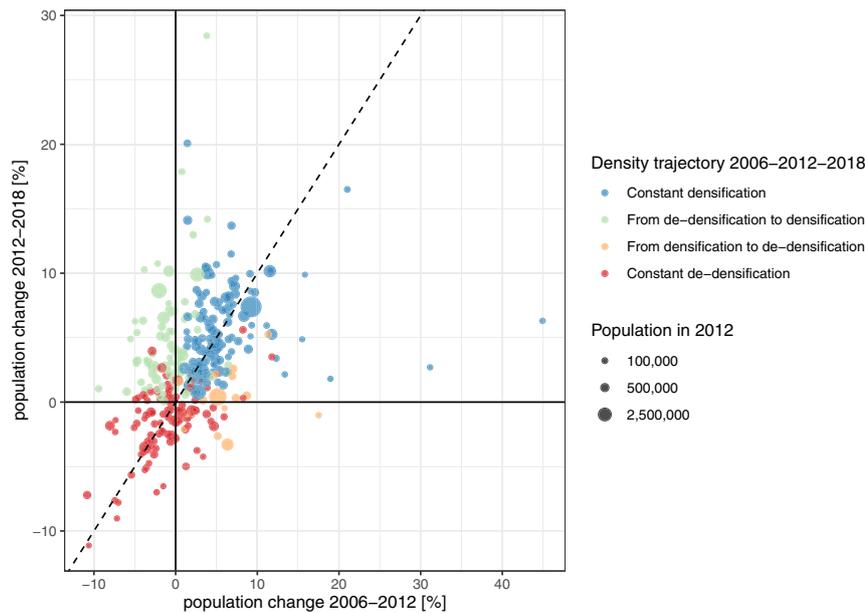


**Fig. 6** Pairwise correlation between density trends and changes in population and residential area. Variables: dens\_ch = change in residential density (persons/ha) during the period, log(pop20xx) = common logarithm of the initial population, dens20xx = initial density, pop\_%ch = percental change in population during the period, nat\_%pop = rate of natural growth calculated over the entire period as percentage of the initial population, mig\_%pop = rate of net migration calculated over the entire period as percentage of the initial population, res\_%ch = percental change in residential area during the period. Values in the panels above the diagonal are the Person correlation and respective significance levels: \*0.05, \*\*0.01, \*\*\*0.001. Panel (a) refers to the period 2006–2012, panel (b) refers to the period 2012–2018.

most recent years appears as a novelty. Previous studies have already identified signals of reurbanization both in US and in European cities. Yet, the trends in US cities described since the 1980s as reurbanization were limited to metropolitan areas and mainly consisted of a renewed population and economic growth, with no implications on the preference for suburban development, and limited impacts on central cities<sup>46,47</sup>. In Europe, after the turn of the millennium, similar urban demographic and economic dynamics suggested a potential resurgence of

cities<sup>48,49</sup>. However, these trends were neither homogeneous nor prevalent across the continent, and their spatial impact in terms of density has been investigated only in a few cases<sup>50</sup>.

Our results show that, in the last years, both population growth and densification became predominant across Europe. A recent study on 129 European metropolitan regions revealed that, contrary to the past, the population of most inner cities grew faster than that of the respective surrounding areas after 2007<sup>51</sup>. There is also evidence that sprawl in the functional areas of



**Fig. 7 Population changes associated to different density trajectories.** The location of the point in the graph indicates the relationship between population changes in the first (2006–2012) and in the second period (2012–2018). The diagonal line indicates equal population change in both periods. Points below the line correspond to cities with a greater increase (or a smaller decrease) in population in the first period, points above the line correspond to cities with a greater increase (or a smaller decrease) in population in the second period. The further the location of the point from the diagonal line, the greater the difference in population change between the two periods.

European cities have slowed down in the same period<sup>52</sup>. If combined with these findings, our results focused on core cities suggest that, under specific conditions, the reurbanization stage theorized by van den Berg only as a hypothesis to guide sustainability policies<sup>25</sup> can actually become a reality.

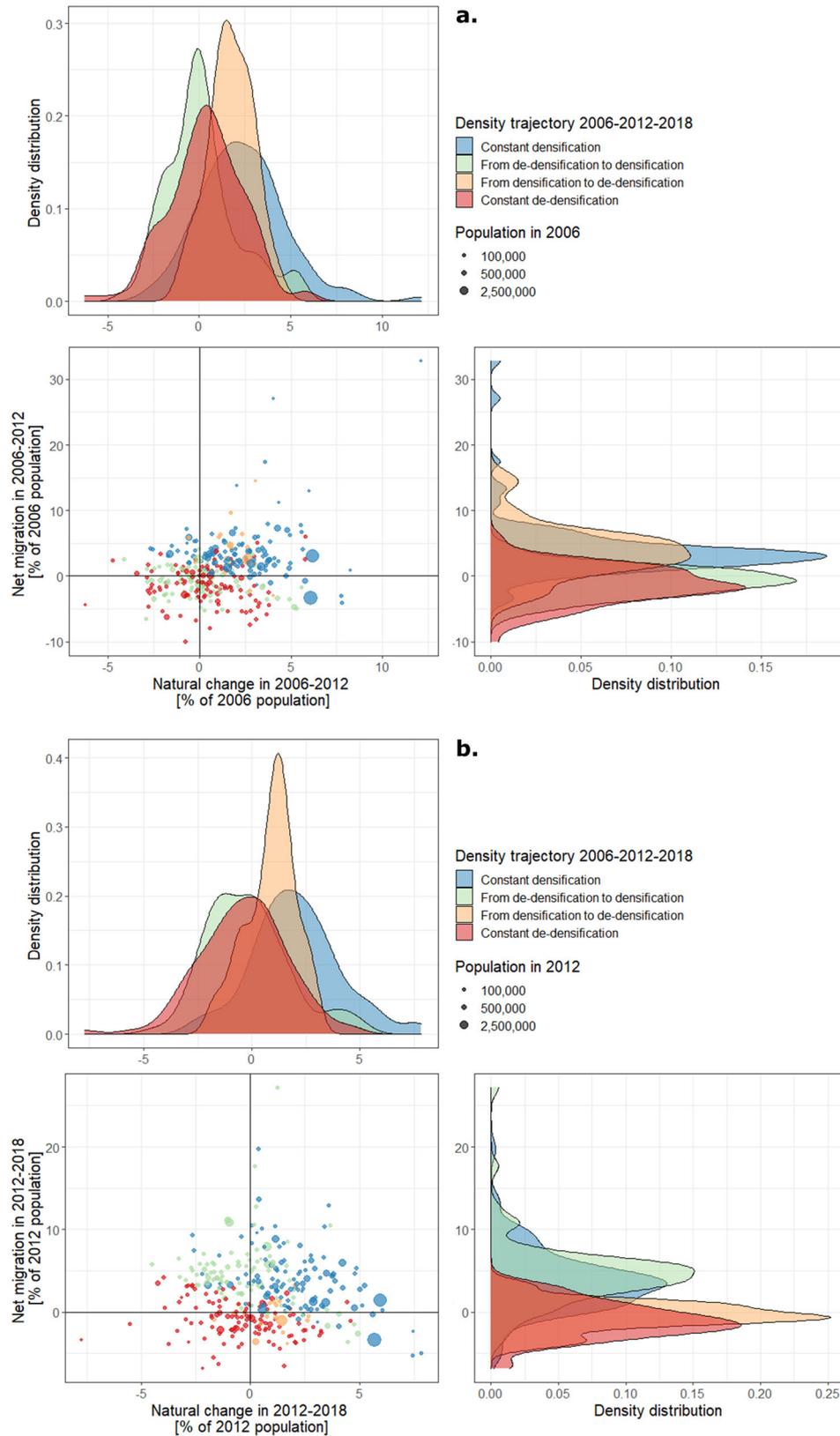
Importantly, population growth and densification are also becoming more widespread across European cities. All regions and size categories include examples of cities shifting from shrinkage to growth and from de-densification to densification. This greater similarity might suggest an increased impact of cohesion policies aimed at reducing disparities across the European Union<sup>16</sup>, but it is also in line with a trend of homogenization of urban areas worldwide, in which migration plays a key role<sup>53</sup>. Nevertheless, clear differences linked to path dependencies of urban development<sup>16</sup> also persist. Most of them confirm the findings of previous studies: the North-South density gradient<sup>54</sup>; the East-West dichotomy that characterized both population trends<sup>48,55</sup> and urban form<sup>56</sup>, as well as the efficiency in the use of land<sup>57</sup>; the fact that large cities grow faster but at the same time use comparatively less land, thus densifying more and shifting more easily from de-densification to densification, while this trajectory is quite uncommon in small cities<sup>20</sup>.

Despite these similarities with known patterns, our study revealed a partly novel picture of density trends. Instead of the East-West dichotomy prevailing before 2012, a longitudinal center-periphery division emerged between 2012 and 2018. This new picture is the consequence of trends that affected almost homogeneously certain countries, such as the shift from de-densification to densification in Italian and German cities. In northern and central Italy, population growth in some urban agglomerations had already started in the first decade of the millennium<sup>34</sup>, pushed by the constant -though slow- increase in the national population until 2015 and by a strong internal migration from the South to the North. Between 2015 and 2018, new migration waves from Mediterranean countries contributed to reverse the de-population trend also in most southern cities<sup>58</sup>. In Germany, only a few cities resisted the widespread shrinkage that accompanied the decrease in national population between

2001 and 2010. But the trend reversed when national population grew again in the following decade, with diffuse growth also in small and medium-sized municipalities, accompanied by a strong suburbanization in city regions<sup>59</sup>.

The opposite trend was observed in Spain. The population boomed between 2001 and 2011 gaining more than 6 million inhabitants. An equally-booming housing sector produced more than 4 million housing units in the same period, largely outpacing the rate of household increase<sup>60</sup>. The bursting of this real estate bubble, combined with the Great Recession after the 2008 financial crisis, forced a reversal of population trends both at the national and at the city level. Between 2011 and 2016, the percentage of cities larger than 250,000 inhabitants with decreasing population changed from 13% in the previous 5-year period to 63%<sup>61</sup>. Despite a noticeable reduction in land take for residential use, the drop in population growth produced a diffuse de-densification also in some cities where density had increased in the previous period.

These cases are emblematic of how trends at the national, continental, or even global level can affect urban development trajectories<sup>49</sup>. In some cases, national policies also seem to have an impact. Examples are planning policies explicitly promoting densification, such as those in place in the Nordic countries<sup>15</sup>, in the UK<sup>62</sup>, and in the Netherlands<sup>63</sup>. Social and family policies can also play a role, such as in France, a unique case among European countries where the population trends of most cities are driven by natural growth. Seven large and medium-sized French cities in our sample shifted from de-densification to densification due to an acceleration in natural growth and in spite of a (sometimes strong) outmigration: a very special trajectory that was not recorded anywhere else. Since the end of the Second World War, a wide range of active family policies has contributed to the high fertility at the basis of these trends<sup>64</sup>. While not all these national specificities are new phenomena, some of the recent ones have partly overwritten consolidated regional patterns of urban development, such as the traditional similarities of southern (including Spanish and Italian) cities<sup>16</sup>.



Against the variety of factors affecting population and urbanization trends at multiple scales, it is difficult to assign a unique and clear meaning to the two periods, whose selection was driven by the availability of high-resolution land use land

cover data. Even though the end of the first period coincided with the approval of the 'no net land take' strategy, it is unlikely that the latter played a major role in the strong drop of land take observed after 2012. The strategy is non-binding and only few

**Fig. 8 Comparison between the two components of population growth in European cities characterized by different density trajectories.** The scatterplots show the values of natural change (on the x-axis) and net migration (on the y-axis) that characterized cities following different density trajectories. The curves show for each density trajectory the distribution (based on kernel density estimation) of the values of natural change (above the scatterplot) and net migration (to the right of the scatterplot). The peak of the curve corresponds to the most frequent value. Panel (a) refers to the first period (2006–2012), panel (b) to the second period (2012–2018). A comparison of the two panels reveals relevant changes in net migration associated to a shift from de-densification and, to a smaller extent, from densification to de-densification (green and orange curves in the density plots to the right).

Member States set national targets right after the approval<sup>65</sup>. The same European Commission proposed a tool to mainstream the ‘no net land take’ strategy only in 2014 with the revision of the Environmental Impact Assessment directive (Directive 2014/52/EU, Art. 3)<sup>66</sup>. More probably, most of the difference in land take rates between the two periods can be attributed to the global financial crisis of 2007–2008 and the subsequent economic recession and debt crisis that hit several Member States. However, the impacts of the crisis were not homogeneous<sup>67,68</sup>, and most countries were already recovering in 2015<sup>69</sup>. Thus, it remains a question whether the reduced land take recorded over the 6-year period was just an immediate consequence of the crisis or a more long-lasting trend.

Our results also show that, irrespective of the initial trend, a large variation in population growth is usually needed to reverse de-densification. Cities characterized by a constant rate of population increase (or decrease) almost always continued along the same density trajectory. Even a shift from shrinkage to growth did not affect density trends in one third of the cases, when the change was too small. On the contrary, most cities growing and de-densifying turned to densification under an acceleration in population growth. These large variations are usually pushed by migration, since natural change tends to be more stable. A key role of migration as the main driver of urbanization trends had already been postulated in the context of re-urbanizing core cities, based on the observation of individual or few case studies<sup>34,70</sup>. Our results provide evidence on the relationship between migration and spatial development based on a large and varied sample of cities.

Changes in fertility rates, household types, and aging are usually highlighted when referring to the ‘second demographic transition’<sup>29</sup>. But the increased mobility of the population and the reasons behind it are fundamental aspects as well. Migration is today very different from the past: individual choices and preferences<sup>71</sup> and the desire to experience the ‘urban life’ play a key role in the propensity to move to the city<sup>72</sup>. Studies on shrinking cities identified in students and people in search of affordable housing the pioneers of inner-city regrowth<sup>70,72</sup>. However, as observed in both US and European cities, what then makes regrowth the prevalent trend at the city scale is usually a mix of international migrants, young adults, some parts of the middle to upper class, and in general adult-centered families with distinct housing preferences compared to couples with kids<sup>27,73</sup>. Even though, compared to the US, families still seem to play a (minor) role in the reurbanization of some European cities<sup>73,74</sup>, the positive correlation that we observed between natural population change and residential land take supports this interpretation.

By densifying, many cities in the sample could accommodate a great population increase in a short period of time with only little expansion of residential areas. This means that a buffer capacity of unused housing stock was available to satisfy the new demand. In cities with long-lasting densification trends, specific policies, e.g. on urban regeneration, may increase the availability of housing units within the urban boundaries<sup>62,75</sup>. But this is unlikely to be the case in de-densifying cities. A relevant share of empty units and their progressive reuse have been documented in cities shifting from shrinkage to growth. In Leipzig, at the peak of the shrinkage phase in 2000, almost 20% of the housing stock (around 60,000 flats) was unused<sup>28</sup>. In Liverpool vacancy rates reached peaks above 15% in some neighborhoods<sup>76</sup>. However, our results

suggest that a relevant share of unused housing stock might be common also in growing and de-densifying cities, where vacant homes may be a result of suburbanization processes that progressively empty inner-city areas. The higher inertia of built-up areas compared to population has often been advanced to explain the linkage between shrinkage and de-densification<sup>77</sup>. Yet, it probably plays a key role also under fast growth conditions. Therefore, indicators solely based on land take or building activity and overlooking population dynamics might not be able to capture the initial stages of densification.

Considering the potential implications of our results for sustainability policies, the new densification wave that emerged in the last years can be an opportunity to strengthen the implementation of the ‘no net land take’ strategy, thus reducing urbanization pressures on the environment. However, the current drivers are very unstable. Migration trends are pushed by volatile location preferences, and the Covid-19 pandemic might already have contributed to shift housing demand away from cities, especially from high-density neighborhoods<sup>78</sup>. The effects of the crisis on the building sector are temporarily and generally seen as undesirable, hence contrasted by policies supporting economic growth. New policies should therefore find suitable ways to turn these factors into enduring trends. In doing so, the differences that characterize European cities (e.g., in their capacity to attract population) and their contexts must be acknowledged. Further research looking at the effects of urban growth and densification inside the city, including potential processes of gentrification and progressive green space deprivation, as well as in the surrounding areas can support the design of effective policies that halt land take while accounting for the needs of the population.

## METHODS

### Sample selection and grouping

We selected the sample of European cities based on three requirements: i) inclusion in the Eurostat Urban Audit database; ii) coverage by the Urban Atlas in all the three reference years 2006, 2012 and 2018; and iii) availability of data on total population for the reference years, and on births and deaths for the two periods in between, either from the Eurostat or from national statistical offices (see details below). The final sample comprises 331 cities: one third of the 992 cities with more than 50,000 inhabitants in the 28 countries of the pre-Brexit European Union. The lack of Urban Atlas coverage for the year 2006 excluded from the analysis all cities in Croatia, while cities in Ireland, Greece, and Cyprus were excluded due to the lack of demographic data.

To investigate relevant differences across the sample, the cities were classified into groups based on region and size. The region was assigned based on the classification of the respective country by the UN (M49 standard, <https://unstats.un.org/unsd/methodology/m49/>), which distinguishes between northern, southern, eastern, and western Europe. The classification by size distinguishes between large cities with more than 500,000 inhabitants (in 2018), medium-sized cities with population between 100,000 and 500,000, and small cities with less than 100,000 inhabitants. Overall, the sample provides a balanced representation of European cities in terms of both regions and sizes. The interplay of the two factors (i.e., region and size) in defining clusters of cities with similar changes in density, population, and residential area was analyzed using regression trees based on ANOVA, which are reported in the Supplementary Figs. 5–7.

## Definitions and calculation methods for the indicators

The analysis was conducted on the density trends and the underlying trends in population and residential area during the two periods 2006–2012 and 2012–2018. Density trends were calculated as the difference in density between two reference years. Densification is defined as an increase in density, while de-densification is the opposite trend. As previously done by other authors<sup>20</sup>, we preferred the more neutral term ‘de-densification’ to the term ‘sprawl’. De-densification does not necessarily imply a change in residential area, while sprawl is usually conceptualized as a process of low-density suburban development involving land take and landscape fragmentation<sup>17,79</sup>. Density is defined as the number of inhabitants per unit area (data are provided as persons per hectare). We chose residential density, i.e. the number of inhabitants divided by the total residential area of the city, as the most meaningful indicator<sup>20,54</sup>.

Population data were primarily collected from the Eurostat Urban Audit database<sup>44</sup>. The values include the number of residents in each city on the 1<sup>st</sup> of January of 2006, 2012, and 2018, and the yearly number of births and deaths from 2006 to 2018. Data from national statistical offices were used to fill the missing values and to double check the existing ones. Several corrections were made to the original database in this step. Throughout the paper, the term ‘growth’ indicates an increase in population, while the opposite trend is termed ‘shrinkage’. We did not set any threshold to define a ‘stable’ population, since an additional category would have complicated the description of the contributions of natural change and net migration.

Natural population change (N) was calculated as the difference between live births and deaths in the period between two reference years (Eq. 1, where  $b_i$  and  $d_i$  respectively are the number of birth and deaths during year  $i$ , while  $a$  and  $\omega$  denote the first and the last year of the analyzed period, respectively).

$$N_{(\omega-a)} = \sum_{i=a}^{\omega} b_i - \sum_{i=a}^{\omega} d_i \quad (1)$$

Net migration (M) was calculated as the difference between total population change and natural change during each period (Eq. 2, where P is total population), as commonly done when more detailed data are not available<sup>32</sup>.

$$M_{(\omega-a)} = P_{\omega} - P_a - N_{(\omega-a)} \quad (2)$$

Residential area and related changes were retrieved from the Urban Atlas database, which provides comparable land use land cover maps of European cities and functional urban areas for the years 2006, 2012, and 2018. We calculated the total residential area of each city by selecting the polygons with land use codes from 11100 to 11300, and summing their area.

The analyses refer to the administrative boundaries of the city (‘core cities’ in the Eurostat’s definition). In the case of urban centers stretching beyond the administrative boundaries, the Urban Audit also identifies the so-called ‘greater cities’. Whenever both land use land cover and population data were available, we substituted administrative boundaries with the corresponding greater city boundaries. This was possible in 28 cases (Fig. 1). Demographic data for greater cities were reconstructed from national statistics by summing the values of all the local administrative units included within the greater city boundary.

Data analysis and visualization were performed in R v.4.0.3<sup>80</sup> and in QGIS v.3.16.10. We used the *psych* package<sup>81</sup> for correlation analysis and the *rpart* package<sup>82</sup> to create the regression trees.

## DATA AVAILABILITY

Population data were collected from the Eurostat Urban Audit (<https://ec.europa.eu/eurostat/web/cities/data/database>) and from national statistical offices. The numerous corrections to the original Urban Audit database and the final source of each value are indicated in the complete dataset that is available in figshare with the identifier <https://doi.org/10.6084/m9.figshare.19773049>. Residential area and related changes were retrieved from the Urban Atlas (<https://land.copernicus.eu/local/urban-atlas>) version 021 for the reference year 2012, version 012 for the reference year 2018, and the consolidated ‘Revised’ version available in 2021 for the reference year 2006. Cities’ and greater cities’ boundaries were retrieved from the GISCO Eurostat spatial database linked to the Urban Audit, version 2018 (<https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units/urban-audit>).

## CODE AVAILABILITY

The code used to analyze the data and to generate the graphs included in the article is available in figshare with the identifier <https://doi.org/10.6084/m9.figshare.19773151>.

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## AUTHOR CONTRIBUTIONS

C.C., D.G., and D.H. designed the study; C.C. collected data and performed the analyses; C.C., D.G., and D.H. interpreted the results. C.C. wrote the paper and prepared the figures; D.G. and D.H. revised and edited the manuscript. All authors approved the final version of the article.

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## COMPETING INTERESTS

The authors declare no competing interests.

## ADDITIONAL INFORMATION

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