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Measuring sustainable urban development in residential areas of the 20 biggest Finnish cities

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As a result of the ongoing urbanization megatrend, cities have an increasingly critical role in the search for sustainability. To create sustainable strategies for cities and to follow up if they induce desired effects proper metrics on the inter and intra-urban development is needed. In this paper, we analyze the sustainability development in the 20 largest cities in Finland through a residential area classification framework. The results based on high-quality register data show concerning trends in some sustainability measures, and divergent trends between cities and residential areas within. Overall, while densities have increased modestly, we see no clear signs of decreasing car ownership rates. Further, also manifestations of social sustainability seem to be insufficient in many locations–especially in residential mid-rise areas from the '60s and '70s, and '80s and '90s.

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INTRODUCTION

Despite the recent challenges with the pandemics, urbanization is a strongly ongoing megatrend that emphasizes the increasingly critical role of cities in the search for sustainability, and their significance e.g., in achieving sustainable development goals (SDGs) adopted by the United Nations in 2015[1]. Cities also posit themselves as active players, or in other words, as solutions to multiple problems related to economic, social and ecological sustainability[2]. In practice, the urban sustainability agenda is implemented through urban planning and policies, touching very centrally the residents and neighborhoods where they live in. To create sustainable strategies for attractive residential areas and to follow up if they induce desired effects, quantitative understanding is needed.

The most heated discussion around urban sustainability is perhaps that of urban densification. Density, along with factors such as mixed-use and public transportation, is a key element also in the compact-city approach[3]. High density is said to be effective in reducing the conversion of natural land to urban development[3], which in turn is expected to reduce habitat fragmentation and preserve urban biodiversity. Further, it is either implicitly or explicitly expected to be leading to a larger share of public transportation users and less dependence on private cars. Indeed, it is empirically proven that in denser urban areas, the energy usage and carbon consequences related to transportation and buildings are likely lower[4,5]. In terms of economic and social sustainability, urban areas offer better employment possibilities[6]. However, there are also tensions related to urban sustainability and densification, even if mainstream urban sustainability relies on continuous growth of urban building stock, without questioning its potential negative side-effects[3]. Densification can lead to increased noise and congestion[7], and potential benefits in terms of traffic and energy use can be substituted with higher consumption-based emissions in other categories[4]. Furthermore, in larger and denser urban areas, economic segregation is more usual[8]. Finally, continuous growth of building stock implies also continuing population growth, yet, we also have cities that are shrinking in size[9]. Furthermore, the migration patterns of population can be divergent within city as well[10], further emphasizing the dynamic nature of cities and urbanization processes. To ensure sustainable urban development, we need to understand these dynamics and potential spatial inequalities between urban residential areas and urban populations and to do that, we need both intra-city and inter-city comparisons of relevant urban sustainability measures.

One of the issues that needs to be tackled while analyzing urban development from any perspective is what areal classification to use. The problem is well documented in the literature, tracing all the way back to the Modifiable Areal Unit Problem (MAUP)[11]. Even if the problem of areal definitions is theoretically well recognized, the issue of correct scale is frequently omitted e.g., from discussions in the empirical literature[12]. The problem is relevant both in analyzing the intra-city developments and in comparing city regions. The classification of residential areas most often follows administrative district borders or postal codes, e.g. in ref. [13–15], or a grid of equal squares, most often with a size of 100 m x 100 m, 250 m x 250 m or 1 km x 1 km e.g in ref. [16]. However, the classifications following administrative district borders or postal codes often result in rather large and arbitrary areal definitions that are not comparable between cities. Especially in the smaller towns, the postal codes can be rather large areas with little substantial meaning. In contrast, the grid approach does not follow any natural borders of urban form and results in arbitrarily bounded areas that are often too small to be analyzed as such. Although identical in square meters, these arbitrary grid cells can often be misleading when comparing cities and smaller towns. When comparing cities, the problem has most often been solved with either classifying similar residential areas in population size e.g. in ref. [17] or employing nearest neighbor approaches, where each household or individual is compared to a certain number of geographically nearest neighbors e.g. ref. [18]. Although these approaches limit the biases related to comparability, they do not solve the underlying problem of defining relevant residential areas. Especially in terms of the built environment, these

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approaches can result in quite diverse residential areas although comparable in the sense of similar population size.

In this paper, we characterize urban development and urban sustainability trends across 20 Finnish cities. Our research question is: "How have the biggest cities in Finland developed in terms of sustainability between the years 2000 and 2018?" To answer the question, we created a classification system based on the typical age and type of housing stock found in different residential areas. This classification allowed us to conceptualize and evaluate the development and sustainability performance within each distinct residential area category, as well as to compare similar built environments across the cities. By employing this approach and combining it with register-based data, we can systematically measure and compare urban sustainability across these residential area types, shedding light on the specific strengths and challenges within each context.

We analyze the changes in population, population density, employment rates, and car ownership development in seven different types of residential areas: centers, block of flats from 1950s and before, block of flats from 1960s and 1970s, block of flats from 1980s and 1990s, block of flats from 2000s, low rise neighborhoods built before 2000s, and low-rise neighborhoods built after 2000. The analysis encompasses the 20 largest cities in Finland, covering over 50% of the Finnish population. Understanding how these key urban sustainability aspects have developed in different types of residential areas is essential, as currently, many of the urban sustainability endeavors focus on new developments while lacking a perspective of the development in older residential areas.

Urban scaling theory builds on notion that all cities – across eras, geographies, and cultures – share some fundamental socioeconomic processes as well as certain predictable quantitative properties[19–21]. Often, urban scaling theories focus on the size or scale of the city, and its effect on various socioeconomic networks of interactions in certain physical space[19]. The common concern is that observed or inferred relationships between socioeconomic variables and physical characteristics of urban areas are unjustifiably affected by the choice of spatial unit of analysis, such as the definition of what is urban[22]. Understanding this concern has led to e.g., harmonized definitions of functional urban areas[23] and other similar urban definitions that are applicable to many countries. Indeed, to understand urban developments, a comparative view is often needed, as in today's world, flows of people, capital, information, and resources shape all geographical settings, yet the effects are not universal. However, there is a lack of within-urban area analyses and applicable classifications that allow for tracing the longitudinal development, and those that focus on socioeconomic development rather than sustainability issues[24].

Typologies of structures within cities can be constructed in various ways. For example, theory of urban fabrics derives from the universal travel-time budget and divides cities based on different transportation types and following structures (walking, transit, automobile) and argues that these three types of fabrics are visible in most cities[25]. They argue that understanding these types and their differences can form the basis of statutory and strategic town planning[25]. However, we argue that in addition to transportation, another important aspect of every city is its built environment.

The built environment is the context for the everyday lives of people, thus pivotal for its sustainability outcomes. First, on a global level, the building sector is responsible for approximately one-third of GHG emissions and energy use[26], both through the construction of buildings and above all because of the energy use of the building stock. Second, related to transportation types and their importance, it can be argued that building stock and its qualities is driving also transportation decisions and the use of different mobility options, also when individual or household-level socioeconomics are controlled for[27–29]. From the social sustainability perspective, it is recognized that various social sustainability dimensions are influenced by the built environment at the neighborhood scale[30]. For example, satisfaction with the qualities of built environment is important for the perceived wellbeing of the residents[31] and built environment accessibility has a relationship with physical activity levels[32]. Furthermore, the planning principles and building practices have varied across different eras, and to summarize, the focus has shifted from modernist principles of car-dependency and functional separation to contemporary ideas that emphasize walkability, transit-oriented development, and incorporation of green spaces. Each era thus produces residential areas with distinct characteristics. Collectively, all these factors demonstrate the critical role of the neighborhood-level built environment in shaping urban sustainability, highlighting the need for context-specific analyses.

Comprehensive data from Finnish registries provides a good starting point for research on the built environment. In particular, data from the Monitoring System of Spatial Structure and Urban Form (YKR), which is a spatial grid-based information system maintained by the Finnish Environment Institute, is widely used among city planners and researchers in Finland. In previous literature, the data has been used to analyze e.g., population changes in sparsely populated areas surrounding urban regions[33], commuting patterns in different urban structures[34], development of urban form[35], and travel-related urban zones[36–38]. Furthermore, the previous works by The Finnish Environment Institute have induced various spatial delineations and classifications, such as urban zones and residential areas that are useful for spatial analysis[39]. Yet another noteworthy dataset from Finland is Helsinki Region Travel Time Matrix that provides openly accessible data on travel times and distances by different travel modes[40].

Another related study is Stjernberg's work, where he created a neighborhood typology for the suburban neighborhoods ("lähiö" in Finnish) built in 1960s and 1970s[39]. Our classification approach is akin to his, since Stjernberg relies on the same grid data to classify the grid cells with more than 50 percent of the people living in the blocks of flats from 1960 s and 1970 s as suburbs that were built during the years of rapid urbanization. However, his focus is purely on suburban neighborhoods while other residential area types are ignored. Considering these most closely related previous pieces of work, there has been a definite lack of a comprehensive residential area classification that provides a solid basis for comparing cities in Finland. Neither are the authors aware of that such classifications would exist in other countries. Therefore, we aim to provide a solid framework for follow-up classifications to enable reliable comparison studies across countries. To address this, we use YKR data to introduce a sophisticated residential area classification that not only distinguishes between the residential property types but also recognizes the different eras producing residential areas with different typical characteristic features. Thus, our classification stands apart from more arbitrarily spatially delineated or non-generalizable classifications that do not necessarily pay attention to local characteristics that are relevant from e.g. sustainability perspectives. This allows broad possibilities for analyzing and understanding the development of urban structure.

By European standards, Finnish cities are often considered relatively small and sparsely built. In general, Finland is one of the most sparsely populated countries in Europe, and the Finnish population is geographically unevenly distributed as most Finns live in the southern parts of the country. 72% of Finnish population lives in urban municipalities, 15% semi-urban municipalities, and the remainder of 13% in rural municipalities[41] In 2020, there were 1.3 million residential buildings in Finland. When measured in floor area, single-family houses and duplexes comprised more than 50% of the floor area, blocks of flats around one third and rowhouses some 10%. Blocks of flats dominate in densely populated areas while single-family homes are the most common housing type outside city and district centers[42].

The Finnish housing stock is relatively young as the true urbanization of Finland did not start until the 1950s, and only 20% of the current residential buildings were built before 1960s and less than 10% before 1940s[43]. Some 17% of the existing blocks of flats were built before 1960s, when the majority of housing production consisted of single-family houses.

In the 1960s and 1970s, Finland was experiencing a rapid urbanization, which resulted in a notable increase in urban housing demand[44]. As a result, almost 40% of all current multi-story apartment buildings were constructed in 1960s and 1970s. These housing developments have drawn special attention from researchers and policy makers due to the multiple challenges they have been facing in the past[45] as well as in the recent years[39], such as segregation and technical deterioration. Even if blocks of flats presented a high proportion of Finnish housing production in the 1970s, many single-family houses and row-houses were also built. In total, 35% of the current small-scale housing was built in 1970s and 1980s, and almost 35% of the current housing stock was produced from the beginning of 1960s to the end of 1980s[43].

In 1990s and 2000s, the Finnish housing production was dominated by small-scale housing and the proportion of blocks of flats was around 30% of the housing developments. However, in the 2010s, production of single-family houses and rowhouses decreased while the proportion of blocks of flats increased to more than 40% of the housing developments[43]. Since the beginning of 2010s, the national sustainability targets towards denser urban structure have put pressure on policy makers and urban developers to find ways to enhance the volume of infill developments even if this has proved to be difficult in practice[46]. An important component of these infill strategies is to increase the volume of housing in close vicinity to public transportation to mitigate the use of private cars. In total, housing developments spanning from 1990s to 2010s represent approximately 35% of the current housing stock.

RESULTS

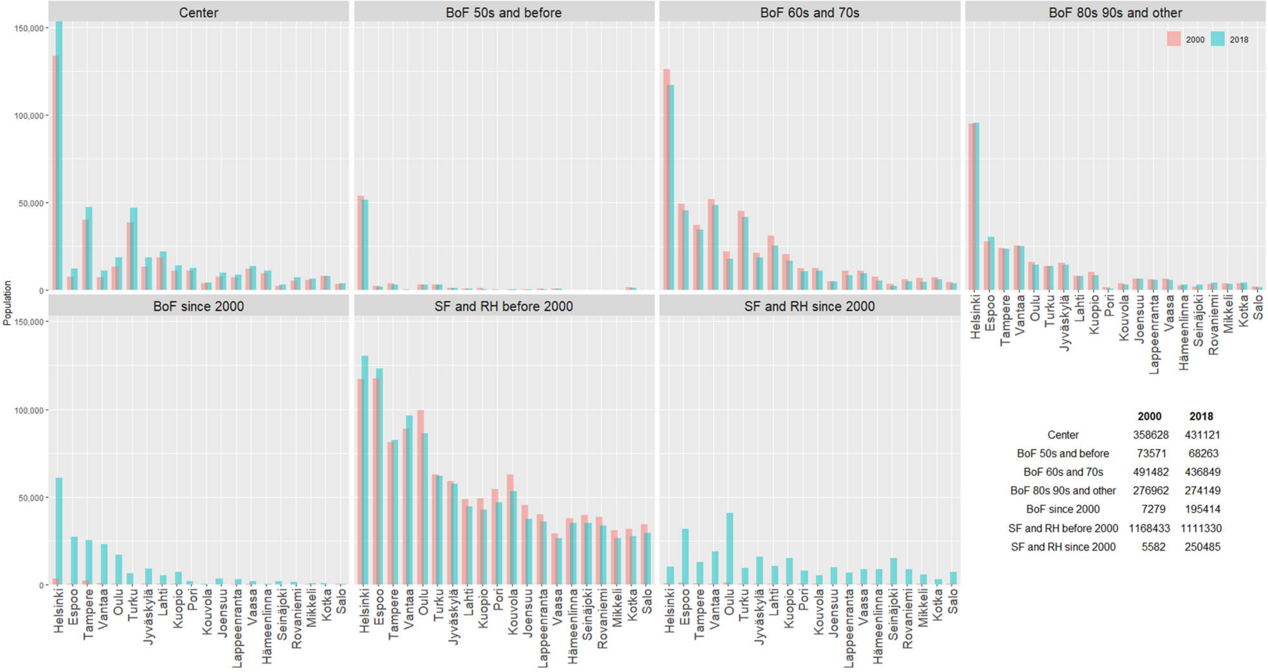
Urban sustainability indicators

We focus on four relevant topics, common among urban sustainability indicators[47], and touching all three main pillars of sustainability. We describe the development of selected indicators between 2000 and 2018 in different residential area types in 20 largest Finnish cities. The order of cities in the following figures is from largest to smallest, starting from the capital Helsinki (total population 648,042 in 2018) and ranging to the smallest city in our sample, Salo (total population 52,321 in 2018)[41]. For other than population amounts, the year 2000 statistics for block of flats since 2000 and for low-rise neighborhoods built after 2000 are not visible due to small number of cases in some cities.

Population development

Population amount matters for sustainability for multiple reasons. The services demanded, infrastructure supplied, and resources consumed in general differ according to the total amount of population, as well as by its rate of growth or decline. For example, housing stock in declining residential areas is underutilized, causing a problem for environmental sustainability, whereas fast-growing areas must ensure social sustainability by balancing the needs of current residents with those of future ones.

There are large differences between the studied cities, in terms of not only the total population, but also on how the population has grown and how it is divided into residential areas, as can be seen from Fig. 1. In almost every city, the most populated class is the older low-rise areas. Even though the number of people living in these areas has been declining in all but the four major cities, most of the Finnish population is still living in such neighborhoods. The dominance of low-rise areas is not only valid for areas built before the year 2000 but also holds true in many cities when comparing proportions of population living in new high- or mid-rise neighborhoods vs. low-rise neighborhoods since the year 2000. In fact, Helsinki is the only city where a clear majority of the population is living in blocks of flats. These observations emphasize that sustainability challenges in the urban context extend beyond the concerns of apartment dwellers, despite them



	2000	2018
Center	358628	431121
BoF 50s and before	73571	68263
BoF 60s and 70s	491482	436849
BoF 80s 90s and other	276962	274149
BoF since 2000	7279	195414
SF and RH before 2000	1168433	1111330
SF and RH since 2000	5582	250485

Fig. 1 Population in 2000 and 2018 in different residential areas and cities. Each barplot depicts populations within a specific residential area class in different cities, and the total population within each class is readable from the box on the bottom right corner.

often being the primary focus of discussions on urban sustainability.

City centers are often central to urban sustainability discussion because they are in many respects closest to compact city ideals. Our classification shows how the population has grown or at least remained steady in all city centers. The increase has been the fastest in major monocentric cities that only have one indisputable city center. On the other hand, Espoo and Vantaa represent more polycentric cities, where the city center targeted population growth is distributed in several urban sub-centers, resulting in relatively lower population growth in the major center, although they are among the group of the four largest cities.

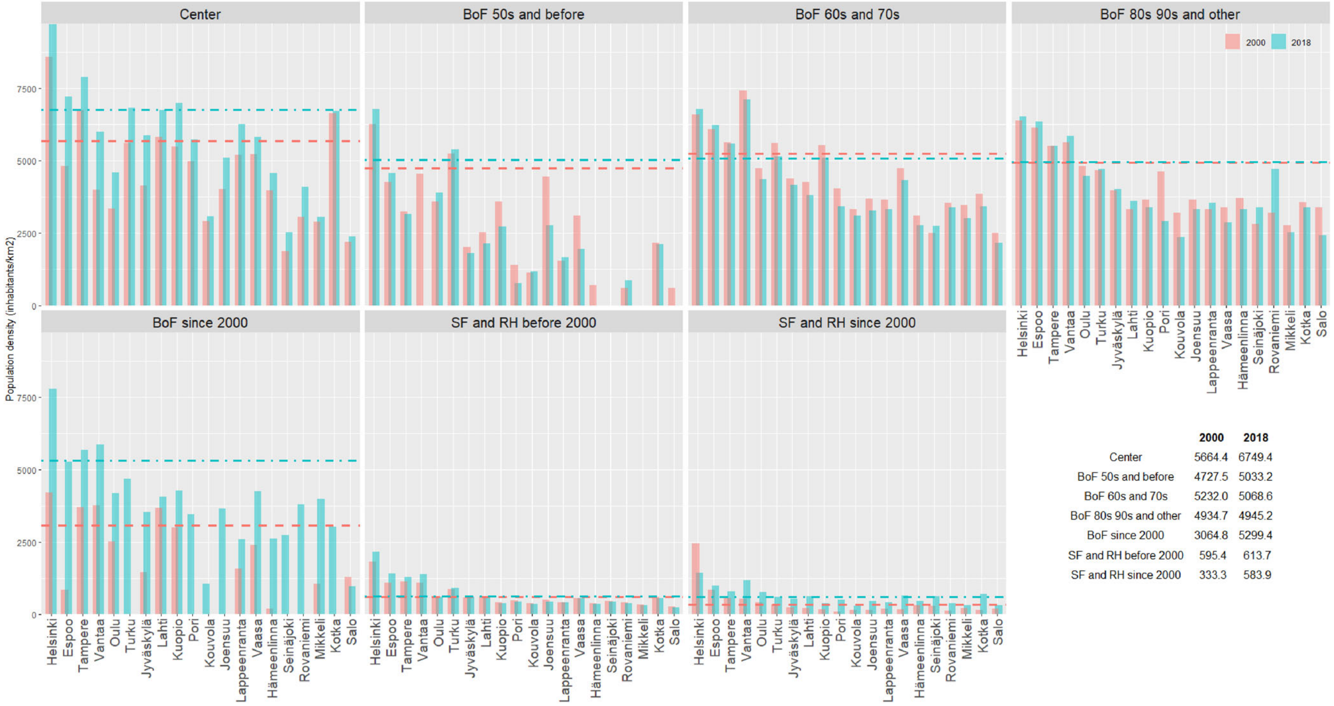
Classification also shows that population growth is not even. Population seems to have declined in all cities in residential areas that are dominated by blocks of flats from the 1960s and 1970s, while it remained rather stable in areas from 1980s and 1990s. However, it is also important to notice that decreasing population development in these neighborhoods is partly attributable to the demographic structure, and potentially also to their falling attraction.

On the contrary, we can naturally observe a surge of population in newly built residential neighborhoods. In 2018, the new low-rise neighborhoods represent a notable proportion in all city sizes, and the proportion of population living in new high- or mid-rise neighborhoods, compared to new low-rise areas, is found to be higher only in Helsinki, Tampere, and Vantaa. Interestingly, new low-rise neighborhoods dominate also the second largest city of Espoo.

Population density

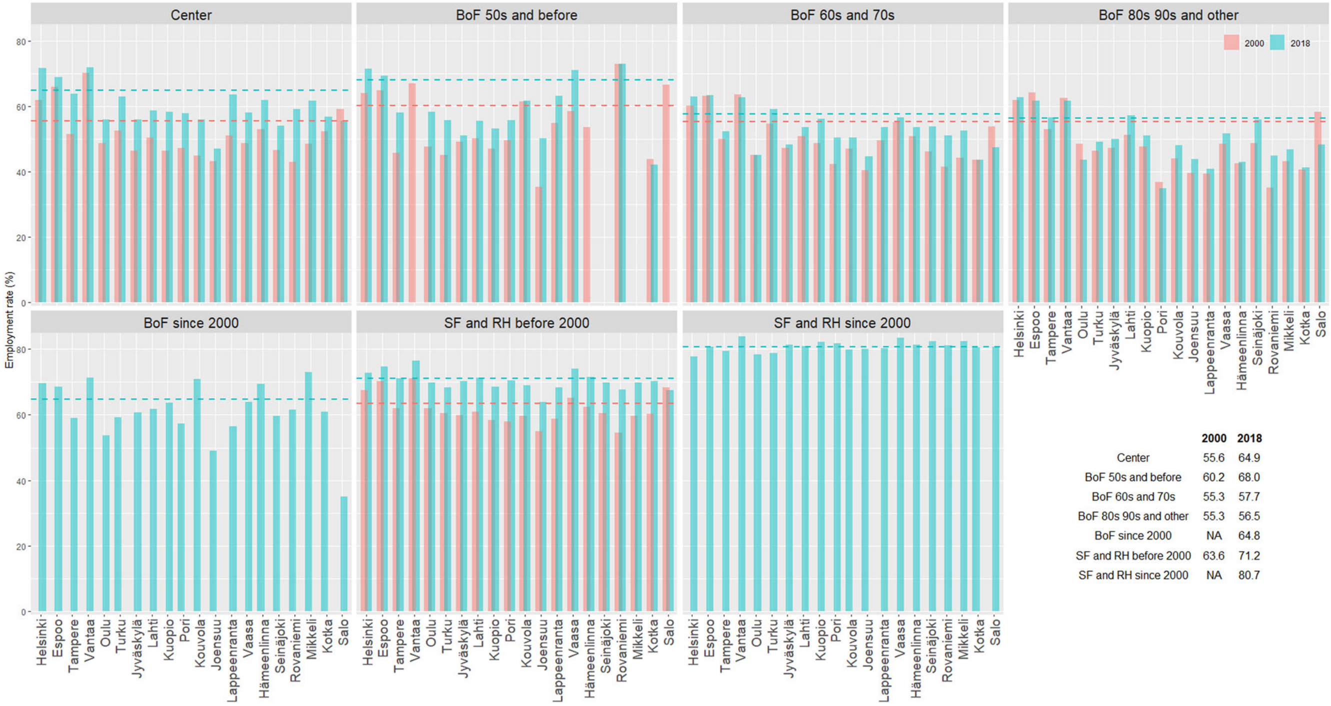
Population density in Finnish cities overall is relatively modest, when compared to many other cities in the world. Still, the density differences between different residential area types are clear, as shown in Fig. 2. The centers are densest of all residential area types, and their density has clearly grown across the board in the study period, on average with almost one fifth. Helsinki has the densest center, as expected, but the centers in many smaller cities are also relatively dense in comparison to ones in much larger cities. When looking at the suburbs from the 60s and 70s, we can see that the average trend is one of decreasing density, apart from the two biggest cities. In the case of Helsinki and Espoo, the growing density relates to the decline in land area of these residential areas between 2000 and 2018. This indicates that these areas have been developed and infill construction volume has been great enough to affect the classification process: in some of the areas, new construction changed the share of 60s and 70s stock to be smaller than 50%, meaning a change in neighborhood class. Overall, the development and the decrease in density relates to decreasing population and housing space in those areas and tells a wider story of how suburban population is growing older and how these residential areas are not attractive to new families. An underlying reason may be new families' unwillingness to move into these areas (e.g. due to bad reputation or different housing preferences of young families), but also older population's inability (e.g. due to the financial situation) or unwillingness to move out from these areas.

Overall, the realized development does not reflect the strong foothold of urban density in the widely pronounced objectives of urban sustainability discussions. For example, in neighborhoods dominated by blocks of flats mostly from 1980s and 1990s, there is no evident trend, as some of these neighborhoods in largest cities have grown denser in the period, whereas in smaller cities there is more variation: in some cities the density is higher and in others lower. In new residential mid- or high-rise neighborhoods, the figures in 2018 show that these areas are denser than older neighborhoods from 60s and 70s, and 80s and 90s, yet less dense than centers in most cases. However, as the development processes in such areas are time-consuming, it might as well be that these areas will still densify in the future. Likewise, when we look at the densities in new low-rise areas, we see that those are slightly less dense than older low-rise areas, which is somewhat surprising, but can again relate to the unfinishedness of these neighborhoods. In older low-rise neighborhoods, the densities



	2000	2018
Center	5664.4	6749.4
BoF 50s and before	4727.5	5033.2
BoF 60s and 70s	5232.0	5068.6
BoF 80s 90s and other	4934.7	4945.2
BoF since 2000	3064.8	5299.4
SF and RH before 2000	595.4	613.7
SF and RH since 2000	333.3	583.9

Fig. 2 Population density (inhabitants per square kilometer) in 2000 and 2018 in different residential area types and cities. Each barplot depicts average densities within a specific residential area class in different cities, and the total average of each class is readable from the box on the bottom right corner.



	2000	2018
Center	55.6	64.9
BoF 50s and before	60.2	68.0
BoF 60s and 70s	55.3	57.7
BoF 80s 90s and other	55.3	56.5
BoF since 2000	NA	64.8
SF and RH before 2000	63.6	71.2
SF and RH since 2000	NA	80.7

Fig. 3 **Employment rate for the working age population (ages 18 to 65) in 2000 and 2018 in different residential areas and cities.** Each barplot depicts the average employment rate of working age populations within a specific residential area class in different cities, and the total average of each class is readable from the box on the bottom right corner.

have slightly grown in biggest cities, whereas in smaller cities the densities have declined a bit.

Employment rate

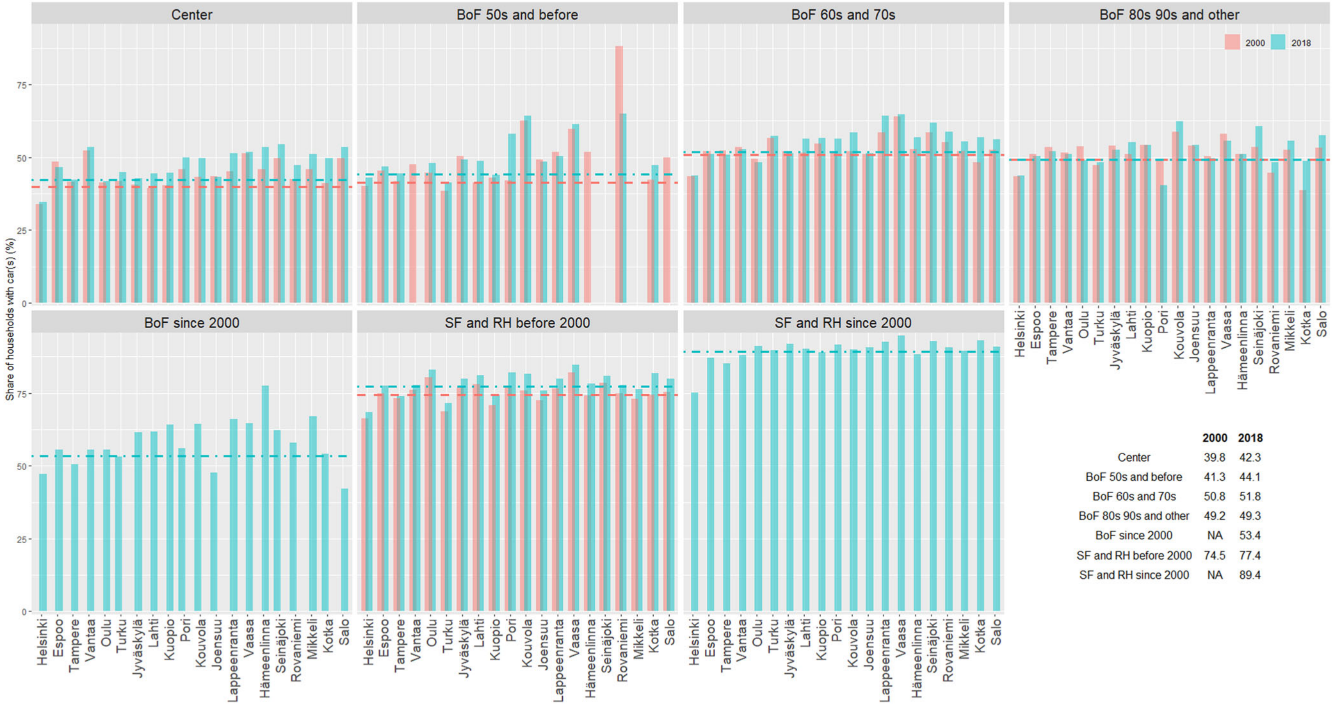
Figure 3 depicts development of employment rates, as employment fosters economic and social well-being, and vice versa, neighborhood-level unemployment has been connected with e.g. higher perceived social disorder[48]. The differences between employment rates between residential areas are not very stark at first glance, yet they have grown over the period between 2000 and 2018. The clearest indication of that is that whereas the average employment rate has grown on average by 8 to 9 percentage points in centers, mid-rise areas from the 50s, as well as in low-rise residential areas, it has grown very modestly, only by 1 or 2 percentage points, in mid-rise areas from the 60s and 70s, and 80s and 90s. As the definition of employment only considers people of working age, the age structure of the population doesn't explain this phenomenon and might link with reduced economic resilience of a typical resident in these areas.

With closer inspection, we also see some noteworthy developments that are relevant for urban social sustainability. For example, in 12 out of all possible city/residential are combinations, the employment rate decreased between the study period. Most of these residential areas are mid-rise areas from the 60s and 70s, and 80s and 90s. Interestingly, city centers in many smaller cities demonstrate better employment rates, and growth, when compared to their counterparts in larger cities. Finally, we see that new low-rise residential areas stand out from the crowd almost across the board, as they have employment rates close to or above eighty percents. From sustainability perspective, this highlights that newer developments are, in many cases, possible only for persons from certain socioeconomic positions. If this is combined with these newer low-rise areas being built more eco-efficiently, risk of so called eco or green gentrification exists[49]. However, new low-rise developments perform more evenly compared with other types of areas, underscoring the significance of urban planning solutions and policies of, for example, social mixing of the population structure aiming to promote social cohesion and reduce segregation.

Car ownership

Figure 4 focuses on one of the central aspects of environmental sustainability, car ownership, and depicts a big picture of constant or increasing popularity of car ownership in all cities and across all neighborhood types. As expected, the average rate is higher in low-rise areas, both old and new, compared to neighborhood types dominated with blocks of flats. When looking at the differences between cities of different sizes, there is a slight tendency of growing car ownership rate towards smaller city size. However, the difference is not as strong as could be expected, when comparing e.g., the public transportation options and availability differences between the bigger and smaller cities in our sample. Helsinki stands out from the crowd the clearest, as it has the lowest absolute share of car owners in all neighborhood types and the growth between 2000 and 2018 is very modest in neighborhood types with older blocks of flats or single-family houses (in the figure, Jyväskylä is smaller in block of flats from 50s and before, but the population amount in that class is only about 1000 residents, making the difference non-meaningful to interpret).

In central Helsinki, the average car ownership rate is clearly the lowest overall, being 33.9% in 2000 and 34.6% in 2018. The only residential area class where car ownership has decreased slightly in many of the cities, especially in the bigger end, is in areas dominated by blocks of flats, mostly from 1980s and 1990s. This can be potentially tracked down to the more central locations of these areas, compared to e.g., new residential developments, as well as the population and its socioeconomic structure inhabiting these areas. When it comes to new developments, both those with blocks of flats and those with low-rise buildings, the conclusion of a relatively high car ownership rate can be drawn, despite the political aims that are often geared towards car free living.



	2000	2018
Center	39.8	42.3
BoF 50s and before	41.3	44.1
BoF 60s and 70s	50.8	51.8
BoF 80s 90s and other	49.2	49.3
BoF since 2000	NA	53.4
SF and RH before 2000	74.5	77.4
SF and RH since 2000	NA	89.4

Fig. 4 Car ownership rate (share of households with at least one car in the household) in 2000 and 2018 in different residential areas and cities. Each barplot depicts average shares of motorized households within a specific residential area class in different cities, and the total average of each class is readable from the box on the bottom right corner.

DISCUSSION

In this paper, we present a framework that allows us to track and compare the sustainability metrics in different types of residential areas and show how 20 biggest cities s have developed in the in the past two decades. In terms of our research question of “How have the biggest cities in Finland developed in terms of sustainability between the years 2000 and 2018?”, there seems to be no unambiguous answer. On the one hand, there are some developments that are promising, but at the same time, the overall picture is lacking a clear indication of urban sustainability improvements. In the following chapters, we highlight the most relevant findings.

Overall, our analysis shows a typical picture of a country with ongoing urbanization. There is both domestic and international migration flows to 20 biggest Finnish cities[50,51]. However, these flows are not evenly distributed between different cities or neighborhoods within them. One of the clear advantages of our classification is that it allows us to estimate the most common living environments in the studied cities. In Finland, around half of the population in the 20 biggest cities lives in low-rise and another half in mid-rise neighborhoods. In terms of change from 2000 to 2018 this ratio has remained quite constant.

The city centers, that in many respects are closest to compact city ideals, have been growing in all cities, and their densities increased. Yet, this development is not reflected in e.g. car ownership rates, which have either remained relatively constant, or more often, increased. On the other hand, even in the biggest cities, we also see that mid-rise neighborhoods from 60s and 70s, as well as those from 80s and 90s to a smaller extent, have lost some of their attractiveness. For example, population declined in all mid-rise suburban neighborhoods from the 60s and 70s in all 20 cities in Finland. In many cities, also the population density decreased, likely due to the ageing population and increasing number of couples in empty nest life course stage. Also, their employment rate growth was almost non-existent over our study period. These neighborhoods and their declining development path are in some respects similar to their European counterparts, mid-twentieth-century large housing estates, which have been linked to a variety of urban problems[52]. In addition, declining development of these neighborhoods exemplifies the sometimes-conflicting nature of different dimensions of sustainability. From the perspective of environmental sustainability, the declining population raises a question of underutilized resources, which calls for revitalization of the existing housing stock, in order to ecologically sustainably make such neighborhoods attractive for new residents. At the same time, from the perspective of economic sustainability, one may ask, if – and to what extent – it is sustainable to use taxpayers’ money to revitalize neighborhoods where market-based conditions for renewal are not met. The future of these housing suburbs is certainly a topic that would merit more research and we hope that our classification will enhance the possibilities for more detailed analyses.

In the Finnish context, residential low-rise areas are of high importance, even though urban sustainability discussion often focusing on high-rise living. Helsinki, Tampere, and Turku are the only cities where clearly less than a half of the population lives in low-rise areas: in Helsinki the proportion is 23 percent while as high as some 40 percent in Tampere and in Turku. In the older low-rise areas, the impact of ageing demographics and empty nest stage of families is important. However, due to infill development, which has been particularly strong in major cities, the residential area level population density has remained at approximately the same level in our study period – or has even increased. In terms of environmental sustainability, it is unfortunate that the share of private car owners is the highest in residential low-rise areas and has increased rather than decreased over the study period, also in the biggest cities where residential density increased in the study period. The future of the residential low-rise areas is closely linked to the decreasing rates of fertility and increased amount of childlessness in Finland[53]. If the number of children continues to fall, the demand for single-family and row houses might fall, as these housing types are preferred by families with children. However, this is especially hard to predict as it depends also on the family formation and partnering patterns of the childless persons that are varying (see ref. [54]). Stable cohabiting or married couples might still be more likely to prefer these housing decisions compared to single households or serial cohabiters.

Smart densification of urban environments is on the agenda of city planners, and we find clear indications of densification, particularly, in city centers and low-rise neighborhoods since 2000. However, to put things into perspective, it is important to emphasize the yet important role of greenfield development in provision of housing. In terms of population, the net loss of population in existing areas has been around 47,000 residents, while greenfield areas have accommodated some 433,000 new residents in the same period. Consequently, more than half (56%) of the greenfield developments are low-rise neighborhoods when measured in population amount. Even if more effective land use is on the sustainability agenda, we do not find higher population densities in the newly developed areas, and their car-ownership rates are among the highest in all classes. Of course, the indicators might still change in the future if these neighborhoods are further developed. Still, our results highlight that many of the sustainability goals of carbon neutral cities are not yet realized, or at least the changes cannot clearly be observed on the level of whole population in the 20 biggest Finnish cities.

In the scope of this article, we are not able to discuss much the mechanisms behind the residential area differences. It is very likely that many of the differences relate to individual level socioeconomic and housing conditions. Here we focused on the residential area differences, but future research could cover more extensively the theoretical and empirical analyses of determinants behind these differences.

All in all, our analysis established the residential area classification framework to be useful in understanding the development of urban areas. Compared to previous classifications, our typology of neighborhoods is especially useful, when analyzing topics that strongly relate to the built environment such as the illustrative examples of population growth, density, and car-ownership demonstrate. However, also socioeconomic development, such as employment we use here, revealed to follow areal patterns. Thus, the classification can be combined with all kinds of spatially explicit data sources, and interesting topics include various aspects related to city planning and urban growth as the built environment is one of the main policy instruments used by the cities[55]. One further advantage of our approach is that, based on the characteristics of housing stock, it has wider availability and thus higher reproducibility compared to classifications based on e.g., residential data. The Finnish high-quality register-based data provided great grounds for developing the classification framework. Still, the classification approach is also widely applicable to other geographic locations, where data availability may be more limited. Then, it is important to pay attention to the local context and heterogeneity of the building stock and adjust the classification criteria accordingly. If there is no other proper local data available, open-source data, such as Open Street Maps, could be used.

Finally, in this paper we look at neighborhoods aggregated to city level, but classification and its potential local applications should be also very usable for both research and practice, whenever detailed information on individual neighborhoods is needed. Policy-wise, our results demonstrate that various aspects of urban growth should be inspected at detailed neighborhood scale, in order to grasp various and sometimes differing developments within a single city. There is a demand for characterizing and measuring the structure of urban landscapes in a way that allows sharing urban strategies effectively[56]. Indeed, our classification can be used to monitor how different neighborhoods are meeting the goals assigned to them, and to compare cities and neighborhoods to each other's, e.g., with respect to ever important urban sustainability aims and related quantifiable targets.

Overall, we highlight some worrying trends in both ecological and social sustainability in Finnish cities. Although there are no major changes in population density the rising car-ownership rates are a potential hazard for environmental sustainability. Further, the differences in employment rates between the different residential areas are rising and potentially creating tensions and undermining social sustainability.

METHODS

Data

We construct residential area classification using data from the Monitoring System for Urban Structure and Form (YKR) (©YKR/SYKE and TK 2018). The data comprises a nationwide statistical grid with a spatial resolution of 250 m. Specifically, the utilized data include a dataset for buildings (©YKR/SYKE and TK 2018) and an open access spatial dataset for city centers and retail areas (©YKR/SYKE and TK 2015).

The dataset for buildings contains information about the building stock in a 250 × 250 m grid, and we utilized information about the residential building types, decades of construction, and living space in each residential building type. In the building register, part of the information was encrypted because of confidentiality reasons in cases where there was only one building in the grid cell. In these cases, the information on building types and years of construction was not available and thus these grid cells are excluded from our classification.

For further analysis of the different residential area types, also YKR grid data on apartment stock, population, households and car ownership were used. For the employment information we use the FIONA remote system module FOLK basic data provided by Statistics Finland. We define residents as employed if they have been employed more than nine months during the year according to the employment registers. For delineation of municipal borders, a spatial dataset from National Land Survey of Finland (2016) was used and thus, the municipal borders remain constant in classifications for different years (in some of the municipalities, there has been several municipal mergers between the years analyzed). The municipality for each grid data point was defined based on which municipality the centroid of a grid cell is within.

Residential area classification principles and definitions

250 × 250 m grid cells were used to create our residential area classification. To reflect the meaningful differences in the built environment, we start with separating areas with the majority of buildings being blocks of flats (BoF) or low-raise single-family and row houses (SF and RH). This distinction is typical to Finnish cities and often a major residential decision people make. BoF residential areas have typically higher population density and offer closer services, and better public transportation. On the flip side, SF and RHs offer larger and more private apartments in more peaceful areas further away from the city center.

The type of dominant housing is not the only possible attribute defining residential area differences. One other aspect relevant to the type of area is the construction year. In the Finnish case this is even more pronounced as over 80 percent of the housing stock was built after the Second World War[43]. The residential areas have typically been built systematically during a short period of time with only a very limited number of older buildings or even later infill development. This has resulted in neighborhoods with very specific characteristics in different decades. Thus, to further reflect the built environment, we classify the cells by the most typical decade of construction (50s or before, 60s or 70s, 80s or 90s, after 2000 for BoF and before and after 2000 for SF and RH).

Table 1. Descriptions and definitions of the residential area classes.

Name	Description	Formal definition	Data sources
Center	An area of mixed activity, with dense population, service and retail jobs	A city center or an urban area's district center (Espoo and Vantaa) in the YKR City Centers classification, and has a YKR grid data point for buildings	YKR City Centers and Retail Areas 2015[57]
BoF 50s and before	A residential mid-rise area dominated by old blocks of flats, mostly from 1950s and before	More than 50% of the floor area* in the grid cell is located in blocks of flats built before the year 1960.	YKR grid data for buildings 2000, 2017[58]
BoF 60s and 70s	A residential mid-rise area dominated by blocks of flats from 1960s and 1970s, often described as suburbs	More than 50% of the floor area* in the grid cell is located in blocks of flats built between the years of 1960 and 1979.	YKR grid data for buildings 2000, 2017[58]
BoF 80s 90s and other	A residential mid-rise area dominated by blocks of flats, mostly from 1980s and 1990s	More than 50% of the floor area* in the grid cell is located in blocks of flats, and there are at least two blocks of flats, and the grid cell is not included in any of the other categories.	YKR grid data for buildings 2000, 2017[58]
BoF since 2000	A residential high- or mid- or high-rise area with mostly new apartment buildings	More than 50% of the floor area* in the grid cell is located in blocks of flats built after the year 2000.	YKR grid data for buildings 2000, 2017[58]
SF and RH before 2000	A residential area dominated by low-rise buildings built before 2000	More than 50% of the floor area* in the grid cell is located in low-rise buildings** built before the year 2000, or the number of low-rise buildings is greater than the number of blocks of flats***.	YKR grid data for buildings 2000, 2017[58]
SF and RH since 2000	A residential area with mostly new low-rise buildings	More than 50% of the floor area* in the grid cell is located in low-rise buildings** built after the year 2000.	YKR grid data for buildings 2000, 2017[58]

All data sources listed are from Finnish Environment Institute.
*Specifically, the total gross floor area of floors that are for housing purposes: attic and basement floors are excluded unless there are apartments in them.
**With low-rise, we refer to all other types of residential buildings than blocks of flats, including single-family houses, duplexes, and row houses; *mid-rise* refers to blocks of flats of up to 12 floors; and *high-rise* is everything above that.
*** The last part of the definition rule *"or the number of low-rise buildings is greater than the number of blocks of flats"* was added based on the feedback received during the collaborative process to better depict the real nature of the area classes. Omitting this addition affects 11,105 grid cells, which is approximately 1% of the classified grid cells.

Last, as the city centers often have a very specific and central role in the urban fabric, we define the city centers as their own residential areas in each city using the ready-made classification of the Finnish environmental institute (©YKR/SYKE and TK 2015)[57].

With this analytical framework relying on the type of most typical buildings, the construction year of the buildings, and on information whether the area belongs to a city center, we define seven classes of residential area types: centers, block of flats from 1950s and before, block of flats from 1960s and 1970s, block of flats from 1980s and 1990s, block of flats from 2000s, low-rise residential areas built before 2000s, and low-rise residential areas built after 2000. The detailed descriptions and classification criteria can be found from the following Table 1.

To describe heterogeneity within the residential area classes, distributions for the proportions of dominating residential building types from the specific eras are presented in Fig. 5. The boxplot shows that there is some heterogeneity within the residential area classes, but in general, the class definitions result in high shares of the dominating housing type from the specific era, confirming that the class definitions are well suited for their purpose. In class SF and RH before 2000, we see some outliers as, based on feedback from the collaborative process with city representatives, the definition rule was modified to also include grid cells, where the number of low-rise buildings is greater than the number of blocks of flats. As the floor area of a single mid-rise building is equal to multiple low-rise buildings, this criterium change results in that we also see grid cells where the relative share of residential low-rise floor area is low. Still, for this class, the median proportion of the dominating housing type is very high. Importantly, for the class BoF 80s, 90s, and other, the figure shows the proportion of mid-rise buildings built in 80s and 90s excluding the other construction years in that class. This confirms that in grid cells that fall into this class, mostly mid-rise buildings from 80s and 90s dominate even if the class definition also allows a wider variety of mid-rise buildings.

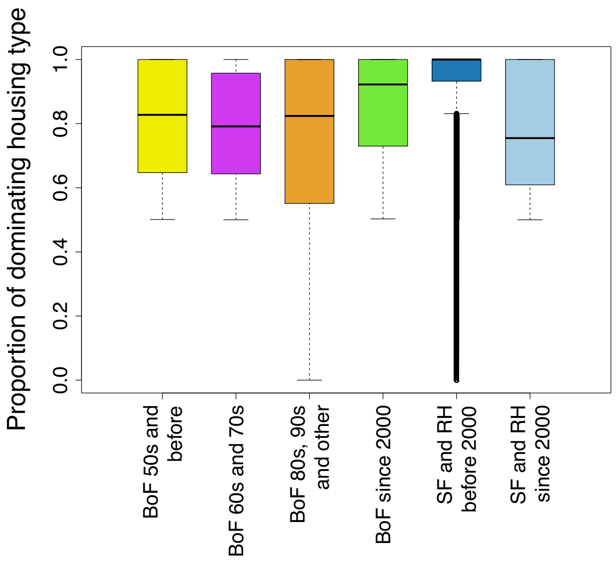


Fig. 5 Heterogeneity of residential area classes. Distributions for the proportions of dominating housing types within the residential area classes. The box's upper and lower limits indicate the range of the data, i.e., ~25% and ~75% of the distribution, and the line inside the box represents the median. Whiskers represent min and max values without outliers. Points are outliers.

There were also grid cells that had data on buildings but did not fall into any of the categories described above and these are not included in our classification. Of these, most were in grid cells where the intended use of the building(s) was something else than residential. In practice, this means that in some of these grid cells, there can also be residential use, but it is not the main type of intended use, as for each building, there is only one main type of intended use. To be classified as a residential building, at least

Table 2. Total population, living areas in different housing types, area density, and number and area of different residential areas in 2000 and 2018.

	Population		Single-family	Row houses	BoFs	Area density	Residential areas	
	number	%	sqkm	sqkm	*sqkm*	floor area/ land area	number	sqkm
2000								
Center	360,200	15.5	0.88	0.61	36.97	2.38	20	63
BoF 50s and before	74,333	3.2	0.10	0.12	6.40	1.35	106	16
BoF 60s and 70s	487,302	21.0	1.56	1.57	37.98	1.35	448	94
BoF 80s 90s and other	277,010	11.9	0.35	0.83	20.53	1.26	385	56
BoF since 2000	7,635	0.3	0.01	0.02	0.59	1.03	27	2
SF and RH before 2000	1,113,691	47.9	63.61	21.48	12.39	0.10	6,765	1,963
SF and RH since 2000	5,070	0.2	0.27	0.14	0.02	0.06	238	17
2018								
Center	**432,778**	**15.6**	0.88	**0.7**	**46.9**	**2.91**	20	**64**
BoF 50s and before	*69,055*	*2.5*	0.10	**0.13**	*6.14*	**1.46**	*90*	*14*
BoF 60s and 70s	*437,074*	*15.7*	**1.63**	*1.56*	**38.04**	**1.47**	*433*	*86*
BoF 80s 90s and other	*275,109*	*9.9*	**0.41**	**1.06**	**23.55**	**1.48**	**402**	*55*
BoF since 2000	**197,853**	**7.1**	**0.17**	**0.47**	**17.78**	**1.67**	**286**	**37**
SF and RH before 2000	**1,115,095**	*40.1*	**76.12**	**25.04**	**18.47**	**0.13**	**6,978**	*1,811*
SF and RH since 2000	**251,664**	**9.1**	**19.16**	**4.59**	**0.85**	**0.09**	**3,383**	**429**

The direction of change between the years 2000–2018 is indicated with font style: italic with underline refers to a decline and bold to an increase.

50% of the living space in the building needs to be dedicated for residential purposes. After this process, there were 35,369 grids in 2000 and 39,932 grids in 2018 classified. Looking at from the population perspective, a total of 83,439 persons (or 3.5% of total population) in year 2000 and 85,872 persons (or 3.0% of total population) in year 2018 in the 20 cities studied were excluded from the residential area classification, and thus from the following analyses.

After the creation of classes, we proceeded to form residential areas based on the classification. After each grid was classified into one of the seven classes, the grids were merged into a single area if two grids shared a border or vertex (queen contiguity). This was repeated until the area had no neighbors in the same category. Finally, there were 7989 (in 2000) and 11,592 (in 2018) residential areas in the 20 cities studied. The municipal boundaries played no role in the merging process, so one area can be on several municipalities (actually, this is the case only in the Helsinki Metropolitan Region, which is the only area where three big cities; the capital Helsinki, and neighboring Espoo and Vantaa; are next to each other). However, when presenting the results on municipal level in Results section the residential areas and grids within including buildings in different municipalities are divided according to the municipal borders, i.e., the buildings and residents are only included in the total numbers and shares of the municipalities where they are located.

Collaborative process

In the process, the classification criteria and the resulting areas were also discussed multiple times with city representatives involved in the SMARTLAND-project, to utilize their hands-on knowledge of their own cities. Before creating the final classification, in addition to previous workshop discussions, we also utilized a GIS-based survey tool Maptionnaire (https://maptionnaire.com/). In this survey, the respondent could comment on the classification criteria and the resulting residential areas. We got 445 comments from 62 separate individuals. Based on these discussions and survey comments the classification criteria was modified, the most important modification being the removal of the sub-center class, as the experts' views on what is a sub-centre were very diverse, and many commented the ones we had to cover areas who truly belonged to some of the other classes defined (typically, some of the BoF 60s and 70s were classified as sub-centers). Thus, the final classification utilized in this paper is thus also based on the valuable hands-on expertise of the city representatives.

Description of the residential area classification

We visualize how the area classification looks in an individual city in the following Fig. 4. Here we can see a typical Finnish city with city center (red) with some connected residential areas of blocks of flats (yellow, purple, brown, green) in the near vicinity. We can see the dominance of single family and row house areas (blue) further away from the city center first as a denser area, but then in a more dispersed manner further away from the center. One should also notice the typical blocks of flats residential areas from the 60s and 70s a bit further away from the city center.

One should note that although the residential areas are often relatively small, consisting of only a few grid cells, some of them can be much larger. This is especially true for low-rise areas build before year 2000 as these residential areas form large, connected networks around the city centers. This should be taken into account when using the classification.

Table 2 tells us more details of the living conditions in Finland and differences between area types. Almost half of urban Finns still live in single-family and row-house-dominated areas, and the number and land area of those types are substantially larger than in residential areas dominated with blocks of flats from different eras. However, comparing only classes with mostly blocks of flats, we can see that especially "the suburbs" from 60s and 70s are quite common in Finnish cities, and their number and land area outrank other types of BoF areas. Table 2 also describes a divergent population development: the population has increased in centers and old low-rise areas, in addition to, quite self-explanatory, also in new high- and low-rise areas. However, despite the general urbanization trend, we see that all other types of areas dominated with blocks of flats (i.e., those from the 50s and before, those from the 60s and 70s, and those from mostly 80s and 90s) have declining population. The loss has been the most substantial in suburbs built between the 60s and 70s, as their total population is 10% smaller

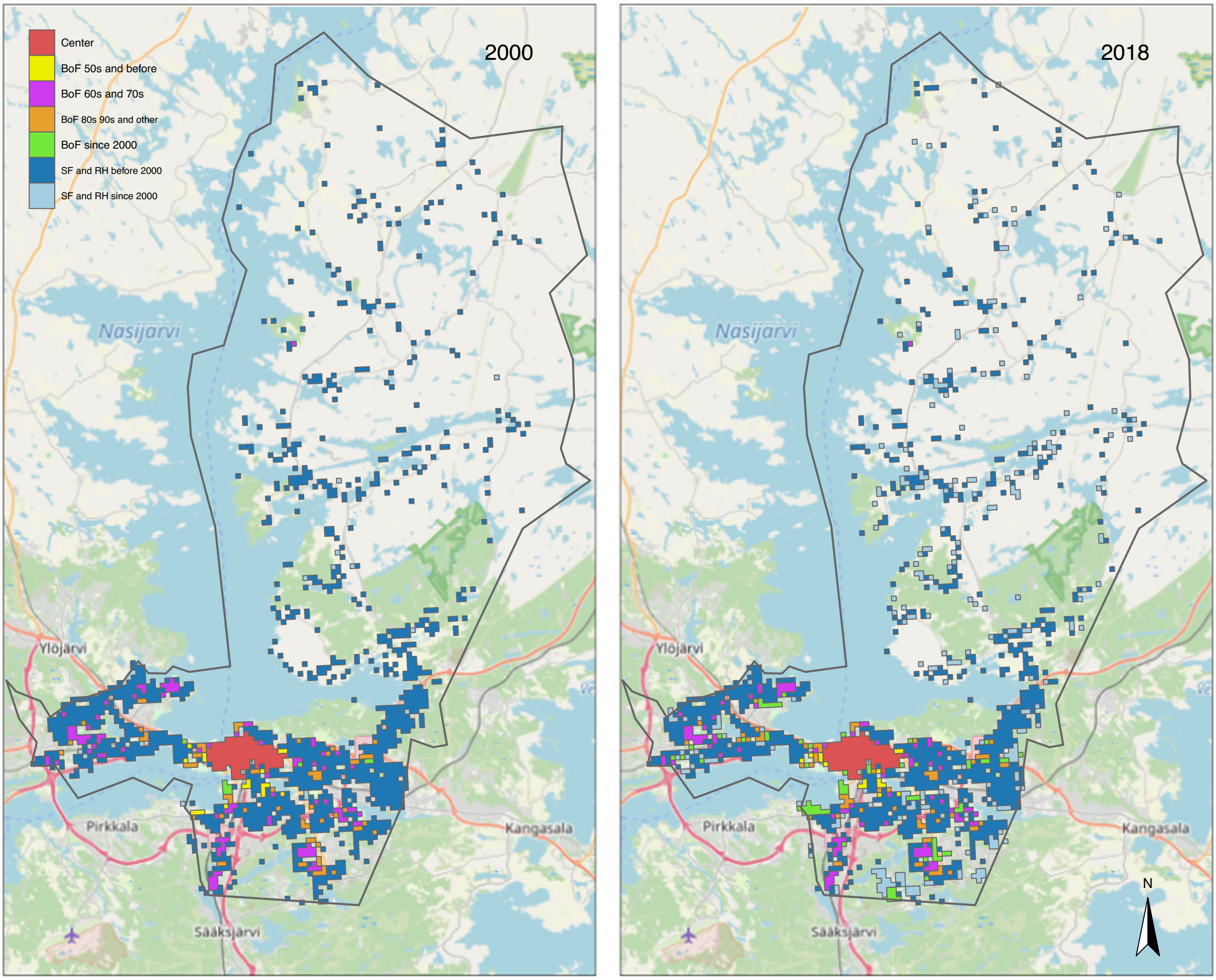


Fig. 6 **Residential area classification in city of Tampere, third largest city of Finland.** Classification in 2000 is on the left-hand side and 2018 on the right-hand side. The municipal borders are drawn with black. The figure data sources are open access data sets from SYKE[57] for city center delineation and municipal borders from National Land Survey[59]. Basemap is from OpenStreetMaps.

than it was at the beginning of the century. From the perspective of housing construction, the most interesting finding is perhaps that the floor area to land area ratio has increased in all area types, but yet it is still relatively low on average (see e.g ref. [58] for descriptions of how different area densities look in practice). If looking at the individual cities, the highest ratio is reported in the capital Helsinki, where the ratio in center is 4.25 in 2018, which is relatively dense (9726 residents per square meter).

A comparison of numbers and areas of different residential area classes shows us that the number of residential areas from 50s and those from 60s and 70s have declined. In practice, this implies that in these areas, also infill construction has happened (and partly also perhaps demolishing), and the area type has changed into another (share of residential living space located in building from these older eras falls below 50%). This kind of development is likely to continue in the future.

DATA AVAILABILITY

The main source of the data is Living environment information service Liiteri (https://www.syke.fi/liiteri/en) that is maintained by the Finnish Environment Institute. The specific datasets we use (buildings, housing stock, population, households and car ownership) are available for contractual customers although subject to a charge. Employment information is available for researchers through the Statistics Finland remote system Fiona in the ready-made module FOLK basic data for contractual customers although subject to a charge. We also utilize an open access spatial dataset for city centers and retail areas (https://wwwd3.ymparisto.fi/d3/gis_data/spesific/keskustatkaupanalueet.zip). For delineation of administrative municipal borders, a spatial dataset produced by National Land Survey of Finland (2016) is acquired from the spatial download service Paituli (https://paituli.csc.fi/download.html). The residential area classification datasets created for this article for both years are openly available in GeoJSON format in Zenodo (https://doi.org/10.5281/zenodo.7416027).

CODE AVAILABILITY

Code available upon reasonable request.

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AUTHOR CONTRIBUTIONS

S.A-M. has developed the idea of residential area classification and the original code used in one city; A.Ku. developed the code further and applied the classification to cover 20 biggest cities in Finland. S.A-M., A.Ku. and A.K. finalized the classification principles. S.A-M., A.Ku. and A.K. interpreted the results and wrote the manuscript. S.A-M. prepared the figures and tables, except for Fig. 5, which was prepared by A.Ku. All authors approved the final version of the article.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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