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Impact of changing urban typologies on residential vegetation and its climate-effects – A case study from Helsinki, Finland

Paula-Kaisa Leppänen [a,c,*], Antti Kinnunen [b], Ranja Hautamäki [c], Leena Järvi [d,e], Minttu Havu [d], Seppo Junnila [b], Outi Tahvonen [a]

[a] HAMK Bio Research Unit, Häme University of Applied Sciences, P.O. Box 230, Hämeenlinna 13101, Finland
[b] Aalto University Department of Built Environment, Otakaari 4, Espoo 02150, Finland
[c] Aalto University, Department of Architecture Otakaari 1X, P.O. Box 11000, Finland
[d] Institute for Atmospheric and Earth System Research, Physics, University of Helsinki, Helsinki, Finland
[e] Helsinki Institute of Sustainability Science, University of Helsinki, Helsinki, Finland

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ABSTRACT

Residential green spaces are an integral part of urban green infrastructure and its role in climate change adaptation and mitigation. Various urban typologies and changing planning practices affect the amount and structure of residential greenery, which has a direct impact on climate benefits. While urban green and its climate benefits have received increasing attention, there is still limited knowledge on how changing planning practices and related urban typologies impact residential vegetation and its capacity to deliver climate benefits. This paper aims to address this gap by determining the impact of planning practices on residential vegetation, focussing specifically on climate mitigation and adaptation. With the case study of Helsinki, characterized by a high share of green areas, the paper first examines how construction year and urban density affect the amount and structure of vegetation on residential properties. Second, it estimates the carbon sequestration and summer temperatures in the present-day climate. The paper applies spatial modelling and regression analysis to estimate the impact of construction year on the studied dependent variables, while controlling density via gross floor area of buildings. The study demonstrates that the average amount of residential vegetation, as measured using canopy and vegetation cover, has declined 15 percentage points from the 1970 s to early 2010 s and the canopy to low vegetation ratio has decreased constantly over the periods studied. The decline of the canopy cover in particular has reduced the climate benefits of residential vegetation. The paper highlights the significant impact of gross floor area and planning practices on urban vegetation cover and the climate benefits it provides. It also stresses the importance of ensuring sufficient tree cover and permeable surfaces in cities with progressive climate mitigation agenda throughout the chain of urban planning, construction, and subsequent property management stages.

1. Introduction

Urban areas comprise a mosaic of green and grey elements, where the amount of vegetation is largely determined by the intensity of development. Green infrastructure is a pivotal component in the urban matrix, as it provides multiple ecosystem services (Niemelä, 2011; Pataki, 2021; Pedersen Zari, 2022) from climate benefits to enhancing public health (Tzoulas et al., 2007; Nutsford, 2013). Over time, societal, economic, technological, and governance transformations have influenced the valuation and integration of urban vegetation within the planning and developmental paradigms (Hautamäki, 2022). For example, current urban expansions alter green spaces through urban sprawl and infill development, affecting both public and private areas (Dallimer et al., 2011; Pauleit and Breuste, 2011).

The scrutiny applied to urban vegetation research is extensive, covering diverse scales from individual trees to expansive public greenspaces, and transcending city boundaries (Neyns and Canters, 2022). Despite the increasing attention, there is still limited knowledge on residential green spaces which occupy a substantial portion of urban land and contribute significantly to the benefits of urban greenery

* Corresponding author at: Aalto University, Department of Architecture Otakaari 1X, P.O. Box 11000, Finland.
E-mail addresses: paula-kaisa.leppanen@hamk.fi, paula-kaisa.leppanen@aalto.fi (P.-K. Leppänen).

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(Loram et al., 2007; Ojala et al., 2017). These areas and their vegetation represent dynamic systems at various developmental stages, influenced by historical land-use, urban planning, and horticultural practices, a phenomenon often referred as the 'legacy effect' (Luck et al., 2009; Raciti et al., 2011; Clarke et al., 2013; Visscher et al., 2016; Trammell et al., 2017). Previous research has also shown that neighbourhood age is a key factor influencing the amount and structure of vegetation in residential urban and suburban neighbourhoods, indicating ecosystem succession at the microscale (Troy et al., 2007; Luck et al., 2009; Lowry et al., 2012).

The spatial configuration of residential properties, particularly the density of building construction, significantly shapes the extent and quality of urban greenery (Godwin et al., 2015; Chen et al., 2020). This is often represented in urban planning metrics as the Gross Floor Area (GFA). A higher GFA typically necessitates more surface area within a property and highlights the need to accommodate essential infrastructure: higher amount of floor area and number of inhabitants increases the demand for parking lots, emergency access roads and recreational areas, reducing the space available for urban green. Consequently, GFA not only quantifies the built-up area but also reflects the economic forces shaping the urban landscape. In areas with high land values, developers often prioritise space efficiency over land acquisition, leading to the prevalence of high GFA developments and contributing to urban densification (Bostic et al., 2007; Brueckner, 2011).

Simultaneously, the planet faces rising temperatures attributed primarily to anthropogenic greenhouse gas emissions, a substantial portion of which originate from urban centres (Marcotullio et al., 2013). In response to the dual pressures of urbanisation and climate change, numerous cities are striving for carbon neutrality or negativity through strategies encompassing emission reductions, compensation, and enhancing urban carbon sinks. The implications for urban land use are needed, as the UN forecasts that by 2050, approximately 70% of the world's population will reside in urban environments—a figure poised to approach 90% in affluent nations (United Nations, 2019). These ambitions are thus being recognised at the higher decision-making level as of late. For instance, the European Union's biodiversity strategy for 2030, accompanied by the proposal for a Nature Restoration Law, acknowledges the vital role of urban green areas and identifies urban green spaces and tree canopy cover in particular as a pivotal element in restoring and maintaining ecosystem services and monitoring the EU's biodiversity strategy (European Commission, 2021; (European Council, 2023).

Currently, the most readily available means to promote carbon sinks, climate adaptation and other ecosystem services in urban areas is preserving and enhancing green spaces (Pataki et al., 2021; Kinnunen et al., 2022; Pedersen Zari et al., 2022; Ariluoma et al., 2023; Kuittinen et al., 2023). Providing these services is closely tied to vegetation characteristics, including the layers formed by trees and bush cover, soil, and impermeable surfaces (Smith et al., 2005; Tratalos et al., 2007; Threlfall et al., 2016). Moreover, providing suitable growing conditions and appropriate maintenance and management are vital for the survival and well-being of urban vegetation (Roman et al., 2014; Hilbert et al., 2019), thereby influencing the ecosystem services they provide (Niemelä et al., 2011; Threlfall et al., 2016). Residential areas can exert a significant influence on city-wide carbon sequestration and storage (CSS) rates and the mitigation of the urban heat island (UHI) effect, particularly via scalability (Allinson et al., 2016; Tahvonen and Airaksinen, 2018; Ariluoma et al., 2021; Drebs et al., 2023; Kinnunen et al., 2022; Havu et al., 2024).

Despite emerging trends in the literature, the current research is lacking broad, city-level assessments on residential vegetation and the associated climate benefits. This study aims at bridging this knowledge gap by undertaking a comprehensive assessment of urban residential vegetation and the associated climate benefits in relation to GFA and construction year by means of a case study concerning Helsinki, Finland. Our primary objective is to delineate and comprehend the structure of residential vegetation and secondarily to assess the ensuing climate benefits of residential properties in a cold-climate city. Specifically, we seek to address the following knowledge gaps:

1) How has construction year and related urban residential typologies influenced the canopy and vegetation cover?
2) How has the variation in canopy and vegetation cover impacted carbon sequestration and summer temperatures in residential areas?

To achieve these objectives, our research builds upon open-source city-level data and process-based modelling. We examine the current state of vegetation and its related climate impacts in areas built in different time periods. We hypothesise that the amount of vegetation and canopy cover are diminishing in residential areas due to reduced parcel sizes resulting from in-fill development, higher residential densities, and the related increase in impervious surfaces. Such insights into urban vegetation's structure aid in understanding the spatial distribution of ecosystem services throughout urban environments and facilitating informed planning and management practices and guidance for these areas. Moreover, the research provides valuable insights into the impact of densification on climate resilience, a critical challenge in contemporary urban planning.

2. Material and methods

2.1. Study area

The study area covers the municipal area of Helsinki, located in southern Finland (60° 10′ 19″ N, 24° 56′ 29″ E, WGS84, Fig. 1.). In 2021, the population of Helsinki was approximately 660,000 and in 2050 it is expected to be 825,000. At the end of 2021 only 18% of the Helsinki population lived in terraced, detached or semi-detached houses, and around 80% in apartment buildings (Statistics Finland, 2023). The major areas for residential building in Helsinki in the near future are in-fill projects including both storage and traffic areas as well as forested areas to be converted into residential neighbourhoods (Sinkko, 2022). In total, 43% of Helsinki's land area is covered by urban remnant forests and conservation areas, with other green areas covering an additional 14% (HRESA, n.d.). Local differences are, however, considerable.

In Köppen's climate classification scheme, Helsinki is in the Warm-summer (Dfb) zone. The mean annual temperature and precipitation sum in Helsinki are 6.5°C and 653 mm, respectively. No significant differences in precipitation between seasons exist (FMI, 2023).

2.1.1. Main historical periods of Helsinki residential areas

The development of the City of Helsinki reflects the development of the surrounding society. Regarding residential areas, some turning

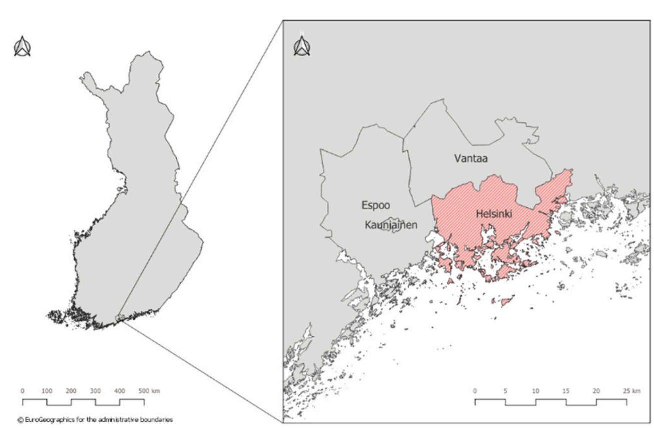

Fig. 1. Location of the study area within Finland.
(Background map: National Land Survey of Finland, 2021; Eurostat, 2020).

points in urban development can be identified from the early 1900 to the present day.

Before the late 1940 s, urban development can be described as pre-suburban. During this time, residential housing was located near the city centre and predominantly comprised dense perimeter blocks. From the 1930 s onwards, functionalism and its ideas for bringing air and natural light into flats opened up the closed block structure (Jalkanen et al., 2017).

After the Second World War, societal changes accelerated urbanisation, leading to the emergence of the suburban era. During this time urban planning first favoured nature-oriented and sparse residential areas (Hautamäki, 2022). Since the 1960 s, the targets of urban planning have shifted to densely built grid plans driven by urban ideals and efficiency. The building volume increased, and the urbanisation proceeded at an accelerating pace, strengthening the urban expansion during the 1970–80 s (Jalkanen et al., 2017).

Since the early 2000 s, the dominant planning paradigm has followed the compact city ideology, which aims to tackle urban sprawl, climate change, and social segregation (Hautamäki, 2022). The compact city has highlighted density and neotraditional urban ideals with perimeter urban blocks. In Helsinki, the compact city era has been characterised by the urban regeneration of former industrial brownfields into housing in the city centre and the densification of the existing urban structure.

2.2. Data

2.2.1. Surface cover data

A raster dataset for land cover classification at a one-metre horizontal resolution (Strömberg et al., 2022) was utilised in this study to map the amount of green areas in Helsinki. The dataset included ten distinct land cover classes. Comparing the classes with aerial images of Helsinki, we observed that areas classified as 'no data' included buildings or transportation areas in terrestrial regions and water bodies in aquatic areas. To address this, we reclassified the 'no data' values (0) as impervious surfaces (2) in terrestrial regions and as water bodies (0) in aquatic areas. Table 1 provides details of the utilised surface cover classes. Distribution of surface cover in Helsinki is presented in Fig. 2a.

2.2.2. Residential properties and buildings data

The dataset of residential properties (Fig. 2b) was derived from the zoning unit data published and maintained by the City of Helsinki (2022a). This dataset contains information about properties for which a purpose of use has been allocated in a valid or pending city plan. Properties were delimited based on their designated use to include only residential low-rise housing (AP) and residential high-rise housing (AK). Residential properties without a distinctly defined purpose of use (A) were excluded from the analysis. In total, the delimited dataset comprised 25,844 individual properties.

The building data used in the study (City of Helsinki, 2022b) were restricted to include only buildings constructed before the end of 2018, aligning with the surface cover data used, and only encompassing buildings situated on the residential properties contained in the zoning unit-data (City of Helsinki, 2022a). The total gross floor area (GFA) and construction year of the buildings served as metrics in the statistical analyses.

Table 1
Surface cover classes derived from the raster by Strömberg et al. (2022). Numerical values and corresponding surface cover classes as well as their proportion of the total Helsinki municipal area are presented in their own columns.

VALUE	CLASSIFICATION	Prop. Of total
0	Waterbody	0.34
1	Open bedrock	0.02
2	Impervious surface	0.10
3	Bare soil	0.08
4	Low vegetation (less than 2 m tall)	0.09
5	Field, farmland	0.03
6	Tree canopy 2–10 m tall	0.11
7	Tree canopy 10–15 m tall	0.08
8	Tree canopy 15–20 m tall	0.08
9	Tree canopy over 20 m tall	0.07

2.2.3. CO_2 flux and summer temperature data

The biogenic CO_2-flux and air temperature data utilised in the study (Fig. 2c–d) were simulated using the Surface Urban Energy and Water balance Scheme-model (SUEWS, Järvi et al., 2011, 2019). Besides calculating the biogenic CO_2 fluxes in μmol m^{-2} s^{-1} or kg C m^{-2} year^{-1}, the model solves the surface water and energy balances, allowing, for example, the calculation of local two-metre air temperature and soil moisture conditions at half hourly-to-hourly temporal resolution. SUEWS divides the urban surface into seven hydrologically connected surface types (buildings, paved surfaces, evergreen trees/shrubs, deciduous trees/shrubs, grass, bare soil and water), and the model needs information about their surface cover fractions and building and tree heights, as well as surface properties. The model is forced using half hour-to-hour meteorological data, including solar radiation, temperature, relative humidity, air pressure, wind speed and precipitation.

The model was run at 250*250 m^2 grid cells for the whole Helsinki area for 2019 with a temporal resolution of 1 hour. The same land use dataset was used to calculate surface characteristics for each grid. For meteorological forcing the MET Nordic dataset (Nipen et al., 2020) consisting of post-processed numerical weather prediction data from MetCoOp Ensemble Prediction System (MEPS, Bengtsson et al., 2017) and meteorological observations were used. For each grid cell, annual cumulative CO_2 fluxes and summertime (June–July) mean temperatures were calculated over 2019. More details of the model runs can be found from Havu et al. (2024).

2.3. Methods

Fig. 3 presents an overview of the methodological approach. The study utilised spatial and statistical analyses to identify residential clusters and then measure or predict the relevant variables within these areas.

2.3.1. Spatial modelling

2.3.1.1. Extracting surface cover metrics. The surface cover data were spatially clipped to measure the corresponding surface cover amounts (in m^2) and proportions per property. This was conducted with R package *exactextractr,* and the surface areas and proportions of each respective surface cover class calculated. The resulting surface cover metrics, along with the mean construction year of the associated buildings and spatial location of each property, were then employed in a spatial clustering analysis. A similar analysis of surface cover was also conducted for each CO_2-flux and summer temperature grid cell. The average construction year of buildings per property was calculated by aggregating the buildings located within each individual property and computing the mean construction year.

2.3.1.2. Spatial clustering analysis. The spatial clustering analysis was performed using R package *dbscan* as hierarchical density-based spatial clustering of applications with noise (HDBSCAN), based on the work of Campello et al. (2013). HDBSCAN is a spatial clustering algorithm that extends the popular DBSCAN (Ester et al., 1996) clustering method by providing hierarchical trees for the resulting clustering solution. These resulting clusters can be combined as based on their relative proximity in the dendrogram if necessary. A minimum set of four properties was required to form a single cluster. The properties were clustered according to their spatial location, surface cover, total surface area,

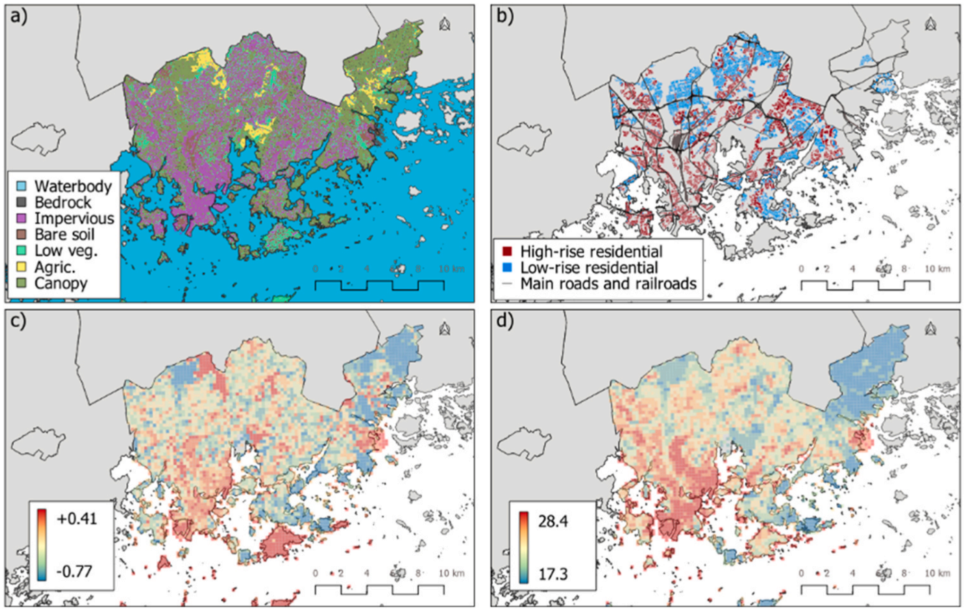

Fig. 2. Maps of the a) utilised surface cover, b) residential properties, c) CO_2 flux (kg C m^{-2} a^{-1}) and d) summer temperature (°C). (Datasets: Strömberg et al., 2022; City of Helsinki, 2022a; Havu et al., 2024. Background map: National Land Survey of Finland, 2021).

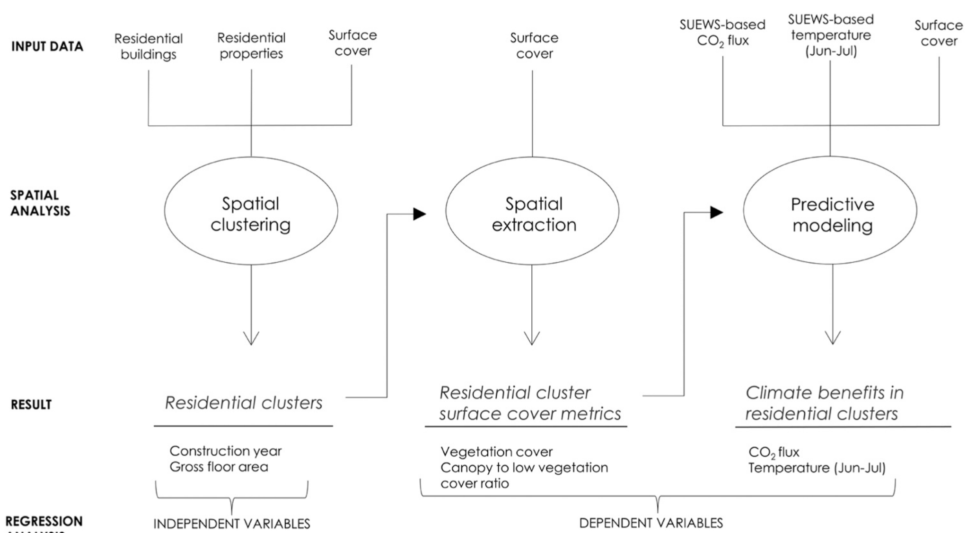

Fig. 3. Depiction of the study's methodological approach. The top row presents the raw input data, while the second row illustrates the spatial-statistical analyses conducted to obtain the outputs described in the third row. The final row explains the use of these outputs in regression analyses to investigate the influence of construction year and gross floor area (independent variables) on the studied impact categories (dependent variables).

construction year and building type (low-rise or high-rise, corresponding to the AP and AK classes introduced in Section 2.2.2). For outlier properties that the algorithm could not assign to a distinct density-based cluster, the nearest neighbour analysis was conducted using R package *nngeo* to integrate them into the nearest applicable clusters within a 250-metre threshold. If no nearest applicable cluster was found, the corresponding property was excluded from the analysis. Once a satisfactory clustering solution was achieved, the surface cover metrics of individual properties within the clusters were summarised together, and proportions of different surface cover classes, as well as the average construction year of buildings and GFA per cluster were recalculated.

The residential properties were initially aggregated into 641 distinct clusters. Among these, cluster 0 comprised properties for which the algorithm could not reliably estimate a distinct cluster, including 732 individual properties out of the total 25,844. Following the nearest neighbour analysis, a total of 207 residential properties remained for which a distinct cluster could not be reliably defined. These were subsequently excluded from the following analyses. The clusters were merged based on their hierarchical distribution and visual inspection. As a result, a final count of 626 clusters was selected as the best representation of the distribution of distinct residential neighbourhoods in Helsinki.

2.3.2. *Statistical analysis*

Statistical analyses were conducted to estimate the influence of various surface cover classes on CO_2 flux and summer temperature in the Helsinki area, predict these variables in residential areas, and observe how GFA and construction year affected them. Likewise, the development of vegetation cover (proportion) and the ratio of trees to low vegetation in relation to GFA and construction year in residential clusters were analysed.

2.3.2.1. Residential CO_2 flux and summer temperatures prediction. The datasets on CO_2 flux and summer temperatures in Helsinki based on Havu et al. (2022) were split into training and validation sets, with 70% of the data comprising the training set and 30% the validation set, corresponding to 2673 and 1146 datapoints, respectively. Cross-validated generalised additive models (GAM) were then fitted to the training data using the R-package *caret*, employing repeated measures k-fold cross-validation with 10 folds and three repetitions to estimate the influence of various surface cover classes on CO_2 flux and summer average temperature. The GAM models were then used to predict these measures in the validation dataset. Model fit and predictive ability were estimated using adjusted R^2-values and Pearson's correlation coefficient between the original and predicted values. After validation, the models were employed to predict the corresponding measures in the residential clusters.

2.3.2.2. Regression of GFA and construction year. Ordinary least-squared linear regression models (OLS) and generalised linear regression models (GLM) were utilised to estimate the influence of GFA and construction year on residential vegetation cover, CO_2 flux, summer temperatures and canopy cover to low vegetation ratio using base R *lm* and *glm* functions. Model fits were estimated using standard adjusted and pseudo-R^2 values according to Guisan and Zimmermann (2000), and statistical significance was interpreted at $p<0.05$, set *a priori* to modelling.

As residential CO_2 flux and summer temperatures conformed approximately to standard normal distribution, the influence of GFA and construction year on them was modelled with OLS-models. The vegetation coverage data were proportional, and consequently, a GLM with a quasibinomial error distribution was employed to construct a corresponding model in this case. The ratio of canopy cover to low vegetation was modelled with GLM utilising gamma error distribution.

2.3.2.3. Residential typologies. To aid in analysing the results and to gain additional insights into the underlying planning and construction practices, the residential clusters were divided into five categories based on their average GFA. These classes reflect the approximate densities of residential areas with various building typologies, characteristic of Helsinki and Finland (e.g. Jalkanen et al., 2017). The clusters were classified into these rough categories (Table 2).

To facilitate the interpretation of the statistical modelling results and gain a deeper understanding of how GFA and construction year interacted and influenced the studied impact categories, GFA, vegetation coverage, canopy cover to low vegetation ratio, CO_2 flux, and mean summer temperatures were standardised utilising Z-scores. Residential clusters were subsequently categorised into ten groups by construction era: pre-1930 structures formed one group, with subsequent decades through the 2010 s each constituting additional groups. The average values of the Z-scaled variables were then calculated for each group and compared along with their variance to shed light on how evolving planning and construction practices over the years may have influenced the development of residential environments in relation to the studied impact categories.

Table 2
Five categories of building typology utilised in classifying the residential clusters based on their gross floor area (GFA).

NAME	GFA	DESCRIPTION	PROP. OF TOTAL
Sparse detached	Under 0.25	Sparsely established one- or two storied buildings, mainly detached but also pair- and rowhouses in some cases.	0.31
Dense detached/ Sparse attached	0.25–0.5	Mainly densely established one- or two storied buildings, potentially some apartment buildings included.	0.27
Sparse attached	0.5–1	Almost exclusively attached buildings, apartment buildings in clear majority.	0.18
Dense attached	1–2	Densely established apartment buildings.	0.10
High density attached	Over 2	High density apartment buildings.	0.14

3. Results

3.1. Determinants of residential CO_2 flux and summer temperature

The cross-validated GAMs were able to effectively capture the influence of individual surface cover parameters on average CO_2 flux and summer temperatures per grid cell, with almost all model parameters exhibiting a statistically significant influence at the predetermined level ($p<0.05$). Regarding the CO_2 flux, all model terms were estimated at a statistically significant level (Table 3). For summer temperature, the model successfully estimated all terms except for fields and farmlands at a statistically significant level. It is noteworthy that the temperature model was unable to reliably estimate the influence of various tree height classes. As a result, individual tree height classes were aggregated into a single parameter for the estimation of the model (Table 3). The adjusted R^2 values of the models were relatively high, with values of 0.929 and 0.801 for CO_2 flux and summer temperature, respectively.

The results of the model evaluation are presented in Fig. 4. Overall, the regression models effectively predicted the original estimated CO_2 fluxes and summer temperatures, with linear associations corresponding to Pearson's correlation coefficient values of 0.96 and 0.9, respectively. Furthermore, the associated error term remained relatively constant across the prediction range, as evidenced by the proximity of individual points to the prediction curve in Fig. 4. Only at the high-end values did the error term appear to slightly decrease in the case of CO_2 flux and increase in the case of summer temperatures. However, given that the observed difference was small and occurred only at the extreme ranges, the validation was considered successful, and the models were used to predict corresponding values for the residential clusters.

Table 3
Results of the GAM-estimation on individual surface cover classes influence on the SUEWS-based average CO_2 flux and summer temperature per grid cell. F-values depict the effect size of individual model parameters and p-values the statistical significance. Adjusted R^2-values indicate model fit to the data.

PARAMETER	F-VALUE	P-VALUE
CO_2 FLUX		
Waterbody	20.489	<0.001***
Open bedrock	16.212	<0.001***
Impervious surface	9.661	<0.001***
Bare soil	6.51	<0.01**
Low vegetation (less than 2 m tall)	17.626	<0.001***
Field, farmland	41.522	<0.001***
Tree canopy 2–10 m tall	12.1	<0.001***
Tree canopy 10–15 m tall	59.754	<0.001***
Tree canopy 15–20 m tall	8.237	<0.001***
Tree canopy over 20 m tall	91.037	<0.001***
Adjusted R^2	0.929	
SUMMER TEMPERATURE		
Waterbody	33.766	<0.001***
Open bedrock	5.024	<0.001***
Impervious surface	20.749	<0.001***
Bare soil	5.462	<0.001***
Low vegetation (less than 2 m tall)	7.469	<0.001***
Field, farmland	1.564	>0.05
Tree canopy (combined)	37.153	<0.001***
Adjusted R^2	0.801	

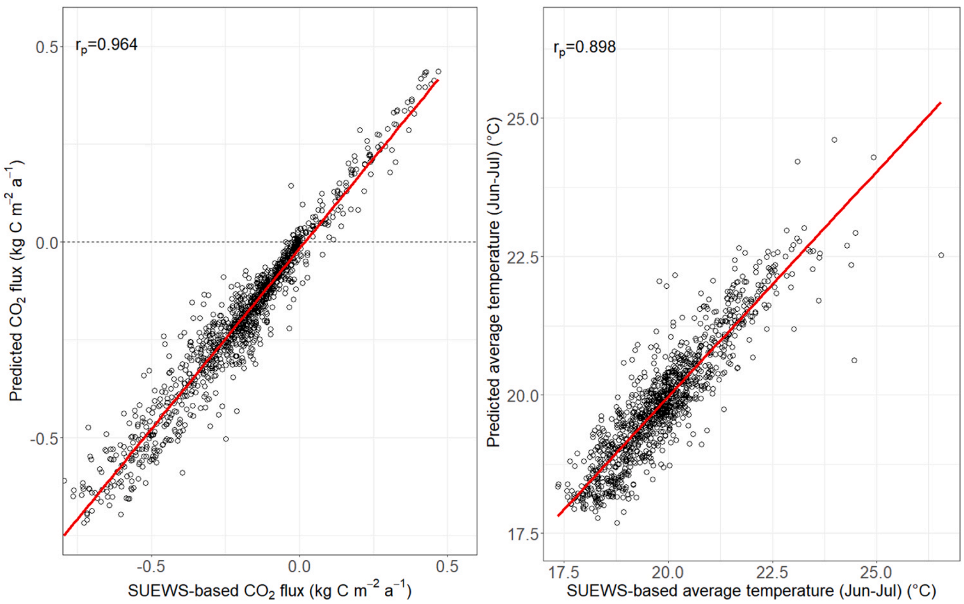

Fig. 4. Results of GAM validation for CO_2 flux (left) and mean summer temperature (right). X-axis represents the SUEWS-based values for CO_2 flux and temperature and y-axis the GAM predicted value. Black circles represent individual datapoints. Linear association between the two values is represented by Pearson's correlation coefficient value (r_p) in the upper left corner and by the red prediction line.

3.2. *Effect of GFA and construction year on the amount of vegetation and climate impacts*

The results of the OLS and GLM analyses are presented in Table 4. These analyses aimed to estimate the impact of construction year on the studied dependent variables while controlling for density via GFA. GFA was incorporated into the models as a logarithmic term. The results indicated that construction year was a significant predictor of all phenomena studied, even when controlling for building density. In most cases, construction year exhibited a quadratic relationship with the dependent variables studied, suggesting that both old and new residential areas exhibited similar trends in relation to vegetation, CO_2 flux and local two-metre air temperature. A notable exception was canopy cover to low vegetation ratio, which displayed a slight yet consistent linear decline over the years. However, this trend was the weakest among those observed, as the model could only explain approximately 30% of the total variance in the data.

Table 4
Results of the regression analyses. T-values depict the effect size and direction and p-values the statistical significance of an individual model parameter. Pseudo- and adjusted R^2-values indicate model fit to the data.

PARAMETER	T-VALUE	P-VALUE
VEGETATION COVER		
Log (GFA)	-30.974	<0.001***
Construction year	11.379	<0.001***
(Construction year)^2	-11.437	<0.001***
Pseudo R^2	0.797	
CANOPY COVER TO LOW VEGETATION RATIO		
Log (GFA)	4.230	<0.001***
Construction year	-12.184	<0.001***
Pseudo R^2	0.291	
CO_2 FLUX		
Log (GFA)	19.794	<0.001***
Construction year	-7.624	<0.001***
(Construction year)^2	7.706	<0.001***
Adjusted R^2	0.601	
SUMMER TEMPERATURE		
Log (GFA)	30.475	<0.001***
Construction year	-7.482	<0.001***
(Construction year)^2	7.501	<0.001***
Adjusted R^2	0.777	

Distinct patterns of clusters with varying mean GFA are evident in the analysis of vegetation cover (Fig. 5a). The historical trajectory of vegetation coverage in Helsinki's residential properties reveals a notable pattern, with an initial increase from very low levels in the early 1900 s to a peak around the 1970 s. Subsequently, a decline followed, somewhat mirroring the earlier increase. Furthermore, a correlation is apparent between the proportion of vegetation and the mean GFA among clusters, as expected; sparsely populated residential areas tend to have more vegetation than high-density areas. Nonetheless, significant differences in vegetation abundance exist with regard to the year of construction (Table 4).

GFA exhibited a positive association with canopy cover to low vegetation ratio, implying that densely populated residential neighbourhoods tended to have a relatively higher ratio of tree coverage to low vegetation in their green spaces compared to sparsely populated neighbourhoods. Conversely, a notable negative trend emerged concerning construction year, suggesting that the proportion of tree cover has diminished, whilst the proportion of open, low-vegetated areas has increased over time in residential neighbourhoods (Table 4 and Fig. 5b).

In the case of residential CO_2 flux, GFA emerged as the most influential predictor. A strong positive relationship was observed between these variables, signifying that densely populated residential areas typically demonstrated lower annual carbon sequestration rates and, in certain instances, even exhibited slight emissions (Table 4 and Fig. 5c). Additionally, the quadratic term of construction year displayed a positive association with CO_2 flux, suggesting that density alone did not account for all of the predicted variability.

GFA also emerged as the most influential individual predictor of residential summer temperatures, exhibiting an even stronger positive relationship than in the case of CO_2 flux. However, once again, construction year remained a significant factor, explaining a substantial portion of the variance in the model (Table 4 and Fig. 5d). In both cases, it appears that residential neighbourhoods with similar GFA experienced lower carbon sequestration rates and higher average summer temperatures in newer developments. This trend was particularly pronounced in neighbourhoods composed of dense detached and sparsely attached buildings, where the positive association with construction year was evident (Fig. 5c and 5d).

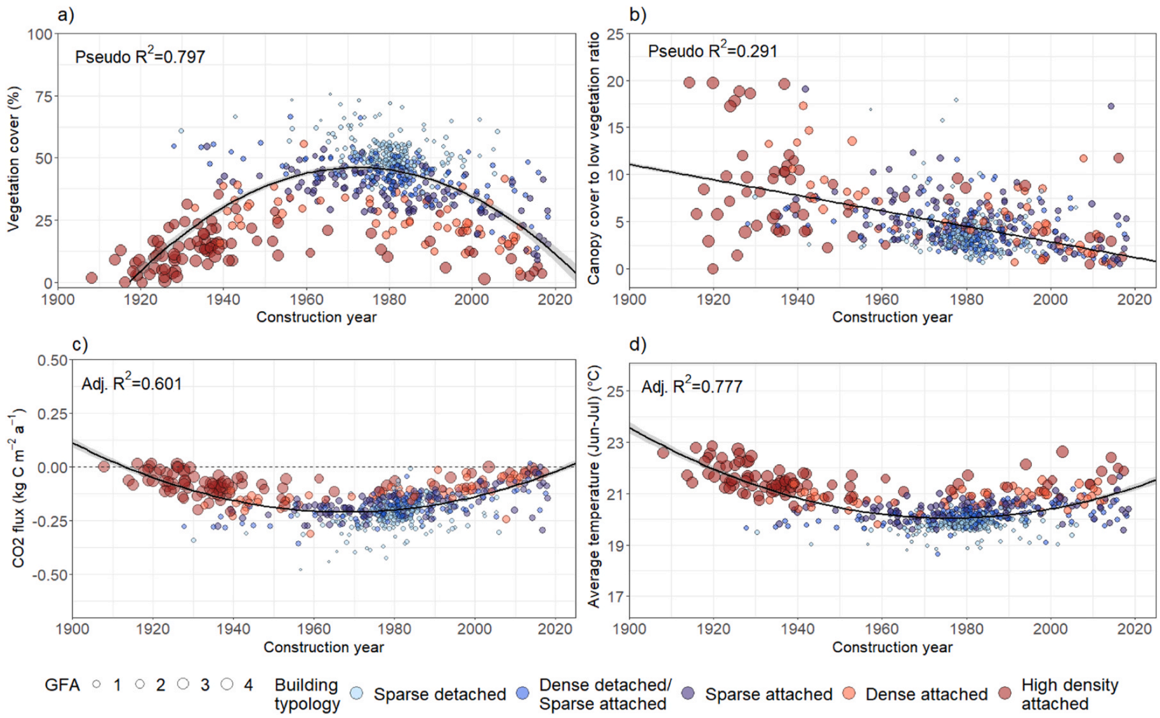

Fig. 5. Regression predicted and SUEWS-modelled values for vegetation coverage (a), canopy cover to low vegetation ratio (b), CO_2 flux (c) and mean summer temperature (d) in the residential clusters of Helsinki by construction year and as a function of gross floor area (GFA) and building typology.

3.3. Variation of residential metrics

The z-scores by construction era of the studied variables are illustrated in Fig. 6. These results mirror the trends identified in the regression analyses, with GFA, vegetation cover, canopy cover to low vegetation ratio, CO_2 flux, and mean summer temperatures closely aligning with the patterns established by the model parameters.

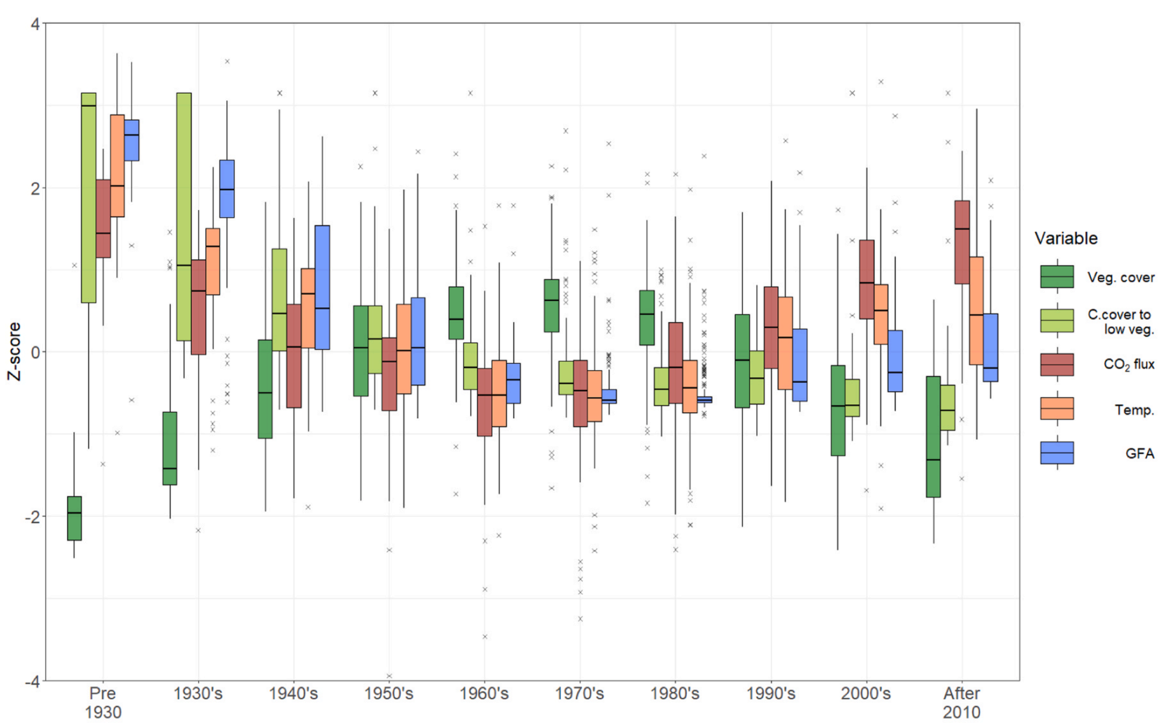

Fig. 6. Variance of metrics across construction eras. X-axis: residential clusters by era; Y-axis: deviation from mean of studied impact categories and GFA. Black lines: median; coloured boxes: 25–75% quartile range; whiskers: data spread. Points beyond whiskers indicate potential outliers. 'Veg. cover' includes all vegetation; 'c. cover to low veg.' compares tree canopy cover to low vegetation.

4. Discussion

In this study we provide a detailed assessment of the urban vegetation in respect to GFA and construction year in Helsinki. The findings are relevant not only for Finnish context but also internationally as cities worldwide face the urgent need to mitigate carbon emissions and alleviate the effects of climate change under the megatrend of urbanization. Firstly, our aim was to identify and understand the structure of residential vegetation in respect to construction year and related urban typologies in cold climate residential properties. We demonstrated that neighbourhood age has a significant impact on the vegetation composition and canopy cover in the study area. Secondly, our aim was to inspect the impact varying canopy and vegetation cover have on the climate benefits produced by the residential properties. Our results showed that the trends on vegetation and canopy cover were reflected in the selected climate benefits provided by the residential properties, with lower rates of canopy and vegetation cover being associated with lowered carbon sink capacity and higher summer temperatures. In the following section, we analyse and discuss the potential causes and implications of the observed results from the perspective of urban typologies.

4.1. Analysis of the residential vegetation of various urban typologies in relation to construction year

The general development of the city and urban planning paradigms are reflected in the vegetation of residential properties. Demographic changes like emigration and rural flight affect land use needs, urban expansion and building typologies. The location of residential areas, GFA and the spatial and architectural configuration of urban blocks and yards, again, shape directly the amount and structure of urban vegetation. In order to discuss the relationship between urban vegetation and urban typologies, we apply the periodisation reflecting the main historical periods of residential areas.

The first, pre-suburban era, where the areas are constructed prior to the end of World War II is characterised by high building density and perimeter urban blocks with very little space for residential vegetation in general, especially in the early 1900 s (Fig. 5a). However, our data shows that the canopy cover in relation to low vegetation is very high in these areas (Fig. 6) suggesting that the existing vegetation consists mainly of mature trees. The residential areas built towards the end of 1940 s reflect the ideas of functionalism in planning and the shift from closed perimeter blocks to more open blocks allowing more vegetation on the properties (Fig. 5a) (Jalkanen et al., 2017).

The residential areas of the second period, the suburban era from the late 1940 s to 1970 s are characterised by an increasing amount of vegetation (Fig. 5a). Our results suggest that the best balance between building efficiency, vegetation and ecosystem services is achieved in the residential areas built during the period from the 1940 s to the 1950 s (Fig. 6). In these areas the GFA as well as the amount of vegetation and especially canopy cover are relatively high, the latter two improving also the resulting climate benefits (Fig. 6). The planning principles of the late 1940 s and the 1950 s reflect the forest city ideology, a Finnish application of the garden city model incorporating existing landscapes and vegetation into urban planning, leading to spacious suburban areas with open block structures and large, lush yards (Hautamäki and Donner, 2021). The model for forest suburbs from this era could thus be re-considered also in contemporary planning in order to maximise climate-related ecosystem benefits within urban development objectives.

In the residential areas built during the third period of the expanding city, from the 1970 s to 2000, the amount of vegetation reaches its peak and starts gradually decreasing from the late 1970 s (Fig. 5a). This period is characterised by two parallel phenomena. First, there is an expansion of detached housing areas which continued until the economic depression and collapse in the Finnish housing market in the early 1990 s (Oikarinen, 2012). The expansion of detached housing is characterised by low GFA, allowing for substantial amounts of vegetation on properties but taking up a lot of space in terms of building efficiency. While the vegetation cover in these areas is high, the relative share of trees is smaller (Fig. 6). In detached housing, the decisions related to vegetation are largely in the hands of residents, which can explain, for example, the absence or removal of big trees (Threlfall et al., 2016; Guo et al., 2019; Klobucar et al., 2021).

Second, parallel to the expansion of detached housing areas, suburban development continued, accompanied by efficient and dense grid plans and the advancements in construction techniques since the 1960 s. Compared to earlier forest city ideology, the dense city allows less possibilities for preserving existing vegetation and also leaves less space for green areas in the properties (Hautamäki, 2022).

The residential areas of the fourth period, the compact city since the early 2000 s, are characterised by infill development and a steady decrease in the amount of vegetation. On the one hand, the compact city aims at tackling urban sprawl and preserving natural areas outside the city, but on the other hand densification has diminished the amount of urban greenery (Hautamäki, 2019). The decreasing trend in urban residential vegetation continues during this period. We presume that one factor contributing to the decrease in residential vegetation is the reduction in parcel sizes. This results in more impervious surfaces, as residential yards in dense urban settings serve multiple purposes like walkways, emergency access routes, maintenance areas, and playgrounds, often paved with synthetic materials.

Based on our data, newly developed, densely built neighbourhoods in Helsinki after 2010 typically have very little vegetation (Fig. 5a). However, it is worth noting that the limited canopy coverage, especially in areas built after 2000, may gradually improve as trees mature. Additionally, the decrease in the amount of vegetation in new residential areas may be due to brownfield development with no pre-existing vegetation, requiring the construction of all green spaces from the ground up. Furthermore, in new developments, the yards are frequently constructed atop parking garages. This creates limitations on vegetation use due to weight restrictions and limited space above and below ground. The limited growing conditions prevent using large trees in planting, resulting in the preference for small to moderately-sized vegetation in yards built above parking garages.

Our results from Helsinki resonate also with international studies. Based on our results, the overall decline of residential vegetation since the late 1970 s is directly dependent on the age of the neighbourhood (Fig. 6), a similar result as Klobucar et al. (2021) obtained in Malmö, Sweden and Lowry et al. (2012) in Salt Lake County, USA. The main assumption in these studies has been that the vegetation, particularly trees, has not had time to grow to its full size. However, the trees used in residential and urban areas can reach their mature size within approximately 20 years (e.g. Kokkonen et al., 2018), suggesting that the growth of the vegetation is not the only explanatory factor. One explanation for the decline of vegetation is that due to, for example, restricted growing space, many tree species now commonly used in residential properties are small- or medium-sized species, as studies from Montreal, Canada (Sousa-Silva et al., 2023) and Great Britain (Monteiro et al., 2020) show. Considering the prior points, the results indicate that the neighbourhoods built since the 1970 s hold a smaller number of trees compared to previously constructed neighbourhoods of similar density (Fig. 6). Therefore, our results imply that urban planning and construction practices have changed since the 1970 s, and the preservation of existing trees on residential properties has become less common compared to earlier periods.

In addition to the tree canopy cover, the decline of vegetation applies also to low vegetation since the 1970 s. Herbaceous plantings, such as lawns and perennials, typically reach their maximum coverage within a few years. Thus, the decrease in low vegetation cannot be attributed to their growth rate. Instead, it can be linked to smaller parcel sizes and an increase in impermeable surfaces, like pavements and terraces. These changes may be driven by shifting consumer preferences and the legacy effects borne out of them. Previous research has explored the influence of historical ownership preferences, yard functionality, and social contagion on plant composition, demonstrating considerable impact on vegetation (e.g., Boone et al., 2010; Hunter and Brown, 2012; Visscher et al., 2016). Additionally, tree canopy seems to mirror past consumption trends, while low-lying vegetation is more aligned with current lifestyle choices (Boone et al., 2010). Our findings resonate with this perspective, suggesting that the observed decline in vegetative coverage from the 1970 s–80 s could be explained by changes in yard functionality, societal norms, and property values, whilst the reduced ratio of canopy cover to low vegetation underpins a historical preference for more arboreal landscapes.

4.2. Impact of canopy and vegetation cover on carbon sequestration and summer temperatures in residential areas

Peak CO_2 sequestration occurs in areas developed a decade prior to those with the highest amount of vegetation, reflecting the abundance of canopy cover relative to low vegetation (Figs. 5 and 6). For example, by comparing the metrics across various construction periods, CO_2 flux is virtually identical in the 1980 s and 1940 s (0.185/0.172 kg C m^{-2} a^{-1} = ratio of 1.08) (Figs. 5c and 6). However, the GFA in the 1980 s is just about a quarter of that in the 1940 s (0.367/1.58 = 0.23), with the canopy-to-low vegetation ratio being less than half of the 1940 s value (3.71/9.27 = 0.4) (Figs. 5b and 6). These insights underscore that, despite a higher percentage of vegetation coverage, residential zones developed in the 1980 s sequester carbon less efficiently relative to their GFA than those from the 1940 s, a discrepancy arising primarily from the vegetative composition. This trend persists from the early to late 20th century: while vegetation coverage rises and GFA decreases, carbon flux rates do not exhibit a corresponding spike, reflecting the declining canopy-to-low vegetation ratio. However, in the transition from the late 20th to the early 21st century, the trend shifts: GFA increases, and vegetation coverage diminishes, likely due to more infill construction and optimised parcel utilisation. Yet, the canopy-to-low vegetation ratio remains stable, leading to plummeting carbon flux rates (Fig. 6).

Modelling outcomes indicate that both GFA and construction year influence summer temperatures in residential neighbourhoods (Table 4, Fig. 5d). The causal mechanism is likely two-fold: a decrease in GFA translates to reduced infrastructure and paved surface requirements, subsequently cooling the adjacent areas. Furthermore, both GFA and the year of construction play a pivotal role in determining the volume and type of vegetation, which, in turn, modulates summer temperatures. The temperature-mitigating properties of urban vegetation have been substantiated by various studies (Pandit and Laband, 2010; Zhou et al., 2011; Li and Wang, 2021) and consistently, our findings highlight that regions with abundant vegetation tend to exhibit cooler temperatures. A significant decline in summer temperatures is observed in residential areas developed in the early to mid-20th century due to the interplay between GFA and vegetation cover. Conversely, areas established in the late 20th and early 21st century show an uptick in GFA and a marked decrease in the canopy-to-low vegetation ratio, leading to soaring summer temperatures. This trend is starkly evident in regions developed post-2000; their mean summer temperatures (20.7 °C) are on par with those of 1940 s neighbourhoods (20.7 °C), even though they possess only slightly over half of the GFA (0.948/1.58 = 0.6) (Figs. 5b, 5d and 6).

Planting a sufficient number of trees of sufficient size is a relatively inexpensive way to mitigate the UHI phenomenon and enhance carbon sequestration in urban areas (e.g. Li and Wang, 2021; Kinnunen et al., 2022). Also, the wellbeing and survivorship of plants are crucial in achieving the desired ecosystem benefits in the long run (Monteiro et al., 2020). However, it is worth noting that tall trees may limit the carbon uptake of lower vegetation (Li and Wang, 2021), and in urban environments, various spaces serve diverse purposes. Furthermore, recent research highlights the significance of low vegetation in terms of ecosystem services (Trémeau et al., 2024), so to maximise benefits provided by the urban vegetation in a balanced way, a diverse set of solutions must be employed to address these challenges.

4.3. Limitations of the study

There are some known limitations in using remote sensing data to map surface cover. For instance, issues like shadow casting and variations in spectral and spatial heterogeneity of materials make vegetation mapping challenging, especially in structurally complex urban areas (Neyns and Canters, 2022). Additionally, some information may remain obscured, as smaller plants are often located beneath a tree canopy. Even when point cloud data from various vegetational layers is used, the final analysis typically focuses on the top layer of data. Nevertheless, the relationship between trees and areas of open, low vegetation can still be discerned.

This research focuses solely on residential properties, recognising that a significant portion of urban greenery exists in public areas. Therefore, the study does not explain the comprehensive planning principles and the total extent of urban green in each period. For example, the limited amount of residential vegetation can be compensated by larger public green areas in the neighbourhood.

We examined the existing vegetation on properties in relation to the year of construction. It is important to acknowledge that the vegetation has evolved over time due to factors like tree and canopy growth, new plantings and plant removals, though these changes cannot be distinguished from the data. However, at the very least, the study setting emphasises the varying amounts of space allocated to vegetation during various time periods.

Additionally, the method employed here does not allow for the differentiation of properties that have undergone in-fill development after their initial construction, potentially introducing some distortion to the findings. However, we believe this distortion is minimal, given that properties from the early 1900 s were already densely built, and infill mainly consisted of adding more floors to existing houses. In cases where spacious properties built, for example, in the 1960 s, were later subdivided, their original land use would mainly underscore the results.

We assumed a uniform composition of surface cover classes across private residential, public, and natural areas. Based on this assumption, we derived the CO_2 flux and temperature metrics. Nonetheless, these metrics may also be influenced by various management practices and vegetation composition in different residential developments (Raciti et al., 2014; Trammell et al., 2020; Trlica et al., 2020). However, as data on maintenance differences was not available from the study region and the underlying CO_2 flux and temperature datasets (Havu et al., 2022) also did not account for these elements, we decided against incorporating them into our analysis.

Our modelling approach aimed to estimate the impact of surface cover classes on CO_2 flux and summer temperatures by simplifying the process-based modelling approach of Havu et al. (2024). This may mean our results lack the fine-scale variability attributable to the chosen methodological approach, potentially affecting their accuracy. However, given the study area's consistent features like climatology, soil, and bedrock composition, the potential error should be minimal.

4.4. Implications for research, policy, and planning

This study provides further insight into how land-use efficiency affects the climate benefits of residential areas. Urban planning needs straightforward tools to optimise climate benefits and other ecosystem services while considering also other needs for city development. Our results show that GFA alone is insufficient in addressing the issue of densifying urban structure sustainably and it is crucial to consider the relationship between the amount and structure of vegetation, and GFA in planning.

Our results contribute to a topical discussion on climate-smart urban planning and the critique on the prevailing compact city paradigm (e.g. Artmann et al., 2019; Balikçi et al., 2022). The findings imply that in progressive, low-carbon cities like Helsinki, efforts to densify urban structure for lower carbon emissions have resulted in new residential zones with less greenery, carbon sequestration, and thermal comfort than older neighbourhoods. These newer areas do not match the densities or the climate benefit levels of the older urban designs. Essentially, current urban carbon mitigation strategies might be leading to a poor compromise of moderate density, low green coverage and reduced environmental quality.

The practical implications of the study are threefold. First, we underscore the need to safeguard existing climate benefits by directing urban growth and land use changes away from areas providing core ecosystem services. Second, when designing new residential areas sufficient greenery has to be ensured, considering both quantity and quality. Third, we advocate for strengthening green structures when refurbishing older neighbourhoods. These strategies are critical for achieving climate neutrality and adaptation goals, enhancing urban biodiversity, and promoting human well-being. They also link to broader urban sustainability issues such as environmental justice and equality, and urge a shift in the urban planning discourse from sustainability towards restorative and regenerative urban systems (e.g. Brown et al., 2020; Camrass, 2022; Lin et al., 2015). The stronger integration of urban planning policies and greening actions is vital in developing resilient urban spaces, a perspective often missing from the density driven discourse (e.g, Artmann et al., 2019; Aquilina and Sheate, 2022; Berghauser Pont et al., 2021).

Our study has also important policy implications. Greening policies for urban ecosystems are highlighted in EU's Biodiversity Strategy 2030 (European Commission, 2021), followed by Nature Restoration Law (European Council, 2023) which establishes green area targets for European cities with focus on green space and tree canopy cover. The law aims at ensuring that biodiversity and ecosystem services are preserved in the urban ecosystems of the member states at the national level. However, our findings reveal that greenery and thus the resulting benefits are not distributed equally across the cityscape. This highlights the need to account for the local level in target setting and to embed residential areas in the provision of green spaces at the city level, instead of focusing solely on regional or national level thresholds.

Supporting residential urban greenery requires new methods and tools, but also a new climate-wise mindset that takes urban green and the climate benefits it provides better into account. For example, it is necessary that climate impact assessment also concerns vegetation and that the land-use decisions are informed by a careful assessment of the impacts of urban planning on urban greenery and related climate benefits. Furthermore, a holistic approach is required that encompasses legislation, planning, design, construction, and maintenance. As cities face the combined challenges of rapid urbanisation and accelerating climate change, they must deal with higher temperatures, extreme weather, and various natural hazards, all of which highlight the need for climate resilience. Future policies and urban planning should focus on strategically incorporating green infrastructure, strengthening urban ecological networks, and integrating crucial ecosystem services into the wider framework of city development.

Our results indicate that more focus is needed to investigate the specific reasons for the loss of vegetation in residential areas. In addition, studies focusing on how different residential vegetation types affect also other ecosystem services, such as biodiversity, stormwater management and health and wellbeing benefits would be extremely valuable to convey a holistic view of the implications of this observed development. These focus points could support the inclusion of residential vegetation as a fundamental component in contemporary urban planning.

5. Conclusions

Understanding how various urban typologies, delineated by construction year and GFA, impact environmental factors in residential areas is crucial for climate-smart urban planning. By examining the relationships between these variables, we can gain insights into how urban design practices and urban typologies influence vegetation, carbon sequestration, and temperature, ultimately contributing to more sustainable and climate-resilient urban development.

Our findings reveal that the nature-inspired planning ideals of the 1940 s and 1950 s seem to best respond to the challenges of both provisioning of ecosystem services and the requirement of dense residential housing. We demonstrate that there has been a dramatic change in the amount and structure of residential vegetation in the late 1970 s–80 s. A significant interaction was identified between urban density and construction year: contemporary neighbourhoods of comparable GFA demonstrated reduced vegetation and tree coverage, decreased carbon sequestration, and elevated summer temperatures, in contrast to their older counterparts. This highlights the need for more integrated understanding of climate mitigation and adaptation in urban systems, stressing the role of vegetation throughout the chain of urban planning, construction, and subsequent property management stages. The legacy of urban planning and ways of construction will be visible in the environment for years and decades to come, so the decisions taken now will have far-reaching impacts.

CRediT authorship contribution statement

Leppanen Paula-Kaisa Leppänen: Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Antti Kinnunen:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Hautamaki Ranja Hautamäki:** Writing – original draft, Supervision, Conceptualization, Funding acquisition, Methodology. **Jarvi Leena Järvi:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Minttu Havu:** Supervision, Data curation. **Seppo Junnila:** Supervision, Funding acquisition. **Outi Tahvonen:** Supervision, Funding acquisition.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT based on OpenAI's GPT-4.0 architecture in order to refine the readability, fluency and grammar of the text. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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