Environmental Research 237 (2023) 116891

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Environmental health impacts and inequalities in green space and air pollution in six medium-sized European cities

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ARTICLE INFO

Handling Editor: Jose L Domingo

Keywords:
Health impact assessment
urban health
Cities
green spaces
air pollution
Equity

ABSTRACT

Background: The GoGreenRoutes project aims to introduce co-created nature-based solutions (NBS) to enhance environmental quality in six medium-sized cities (Burgas, Lahti, Limerick, Tallinn, Umeå, and Versailles). We estimated the mortality and economic impacts attributed to suboptimal exposure to green space and air pollution, economic impacts, and the distribution thereof the adult population by socioeconomic status.

Methods: We retrieved data from publicly accessible databases on green space (NDVI and % Green Area), air pollution (NO_2 and $PM_{2.5}$) and population (≥20 years, n = 804,975) at a 250m × 250m grid-cell level, and mortality for each city for 2015. We compared baseline exposures at the grid-cell to World Health Organization's recommendations and guidelines. We applied a comparative risk assessment to estimate the mortality burden attributable to not achieving the recommendations and guidelines. We estimated attributable mortality distributions and the association with income levels.

Results: We found high variability in air pollution and green spaces levels. Around 60% of the population lacked green space and 90% were exposed to harmful air pollution. Overall, we estimated age-standardized mortality rates varying from 10 (Umeå) to 92 (Burgas) deaths per 100,000 persons attributable to low NDVI levels; 3 (Lahti) to 38 (Burgas) per 100,000 persons to lack of % Green Area; 1 (Umeå) to 88 (Tallinn) per 100,000 persons to exceedances of NO_2 guidelines; and 1 (Umeå) to 206 (Burgas) per 100,000 persons to exceedances of $PM_{2.5}$ guidelines. Lower income associated with higher or lower mortality impacts depending on whether deprived populations lived in the densely constructed, highly-trafficked city centre or greener, less polluted outskirts.

Conclusions: We attributed a considerable mortality burden to lack of green spaces and higher air pollution, which was unevenly distributed across different social groups. NBS and health-promoting initiatives should consider socioeconomic aspects to regenerate urban areas while providing equally good environments.

1. Introduction

It is already well-known that cities can impact population health, by generating adverse environmental conditions (e.g. lack of natural outdoor environments, high air and noise pollution, urban heat island effects). These factors can threaten health and well-being of residents, contributing to diseases and premature mortality (Nieuwenhuijsen, 2016, 2018; World Health Organization, 2018a, 2018b; Pereira Barboza et al., 2021; Khomenko et al., 2021a, 2021b, 2022; Iungman et al., 2023). In Europe, air pollution due to fine ambient particulate matter

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https://doi.org/10.1016/j.envres.2023.116891
Received 2 June 2023; Received in revised form 10 August 2023; Accepted 13 August 2023
Available online 16 August 2023
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with a diameter less than or equal to 2.5 μm ($PM_{2.5}$) and nitrogen dioxide (NO_2) concentrations exceeding the 2021 World Health Organization (WHO) guidelines resulted in 238,000 and 49,000 premature deaths in 2020, respectively (European Environmental Agency, 2022). On the other hand, green spaces such as parks, urban forests, gardens, and street greening can contribute to better relaxation, restauration, mental health, immune functioning and social contacts (European Environment Agency, 2022), reducing the risk of mortality (Rojas-Rueda et al., 2019; Gascon et al., 2016).

Environmental health factors are rarely distributed evenly across the cities' territory (Pereira Barboza et al., 2021; Iungman et al., 2021; Khomenko et al., 2020; Mueller et al., 2017, 2018), hence, exposure to air pollution, noise, heat, and lack of green space at the individual level is determined by the local context of the place of residence and occupation, in addition to transport practices. Moreover, environmental conditions are not equally distributed among different socioeconomic groups in cities, which can lead to double jeopardy of socioeconomic deprivation and harmful environmental exposures, possibly intensifying health burdens (European Environment Agency, 2022; Kihal-Talantikite et al., 2019; Deguen and Zmirou-Navier, 2010). Urban planning policies also affect human behavior in terms of physical activity and social interactions, which are both determinants of physical and mental health and well-being (Nieuwenhuijsen, 2018; de Vries et al., 2013).

Initiatives such as the Green City Accord (European Commission, 2021), European Green Capital Award (European Commission, 2023a), and European Cities Mission (European Commission, 2030) stimulate local authorities to generate local plans, initiatives, and interventions that tackle environmental challenges associated with urban design and transport systems, to reduce adverse impacts and associated inequalities. The regeneration of urban areas through improving the access to and the quality of open green spaces is a strategic initiative for creating healthier environments. Green space interventions can provide several health benefits through encouraging physical activity and fostering social interactions, besides improving environmental conditions (Vert et al., 2019a, 2019b; Hunter et al., 2019), by reducing air pollution, road-traffic noise, and the urban heat island, whist promoting biodiversity and urban resilience.

The health impacts of environmental factors associated with urban and transport planning practices have been estimated through the application of Health Impact Assessments (HIA). HIA can be done at national, subnational and local levels, but until now, most city-specific HIAs in Europe have been performed in big and capital cities (Iungman et al., 2021; Khomenko et al., 2020; Mueller et al., 2017, 2018; Mitsakou et al., 2019), where local scientific evidence and high-quality data tended to be easily available. Hence, medium and small-sized cities lack proper quantification of associated health impacts that can support the definition of evidence-based health-promoting policies and interventions. About 50% of the urban population in Europe lives in medium-sized cities with less than 400,000 inhabitants (Eurostat, 2023), with unique urban features and activities. Therefore, a better understanding of the impacts of environmental exposures on health in medium-sized cities, and how these impacts are distributed within the population are key to provide local evidence for policies towards more sustainable and healthy urban settings.

In this study, we intended to evaluate environmental exposures associated with urban and transport planning (i.e., green space and air pollution) and their health impacts across the population and social groups in six medium-sized European cities, including Burgas (Bulgaria), Lahti (Finland), Limerick (Ireland), Tallinn (Estonia), Umeå (Sweden), and Versailles (France). These cities have different population distribution, urban-design, environmental, and socioeconomic contexts, however, they share a strong ambition in green policies (MacIntyre et al., 2019). Burgas, located in the east of Bulgaria on the Black Sea, is a signatory to the Green City Accord, committed to further action to achieve ambitious goals by 2030 in five areas: air, water, nature-&biodiversity, waste&circular economy, and noise (European Commission, 2021). Lahti, in the south of Finland (i.e., 100 km from Helsinki), was awarded as European Green Capital 2021, is one of the 100 selected cities for the EU Cities Mission for climate-neutral and smart cities by 2030, and is also a signatory of the Green City Accord (European Commission, 2021, 2023a, 2023b). Limerick, located in the west of Ireland (i.e., 60 km from the Atlantic Ocean), was recognized as European Green Leaf City 2020 and is a member of the Health & Greenspace Urbact project for urban green infrastructure for health and well-being (European Commission, 2023c; Health&Greenspace, nd). Tallinn, the capital of Estonia, located on its southern coast (i.e., Gulf of Finland), was granted the title of European Green Capital (2023) and is also a signatory of the Green City Accord (European Commission, 2021, 2023a). Umeå, located in northern Sweden, was a finalist in the European Green Capital Award for several years (i.e. 2016, 2017, 2018) and is also one of the 100 selected cities for the EU Cities Mission (European Commission, 2023a, 2023b). Finally, Versailles is located near Paris and its gardens are the most famous worldwide, which made the city one of the first areas listed among the UNESCO World Heritage sites (UNESCO, 2023).

These six cities are planning to implement distinctive "nature-based solutions" (NBS) such as green corridors, linear parks, pocket parks, and shared walkways to promote equal access to good environmental conditions for local populations, and to enhance the physical and mental health of their urban residents within the European funded GoGreen-Routes project (GoGreenRoutes, nd). NBS are defined by the European Commission as "solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience" (European Commission, 2023a, 2023b, 2023c, 2023d). With this approach, these cities expect to address the nexus that exists between air pollution, green infrastructure and population health to improve environmental conditions (Prashant et al., 2019). For this, local stakeholders are being connected through an iterative co-creation process for the NBS, to discuss and decide on the interventions. Moreover, expected health and economic impacts associated with the interventions will be monitored and assessed (GoGreenRoutes, nd).

Hence, we aimed to estimate the green space and air pollution distribution in each of these six cities and analyze their impacts on mortality and associated economic burden due to suboptimal conditions. Furthermore, we also estimated the mortality impact distribution among the population by socioeconomic status, before the implementation of these NBS. We intend to inform local stakeholders about the current situation of impacts due to suboptimal conditions each city and the socioenvironmental inequalities faced by the local population, as well as provide evidence and recommendations to prioritize future local interventions that promote population and environmental health.

2. Methods

2.1. Study settings

Our study consists of six medium-sized cities mentioned above, located in different European countries: Burgas (Bulgaria), Lahti (Finland), Limerick (Ireland), Tallinn (Estonia), Umeå (Sweden), and Versailles (France). We defined the city boundaries for the six cities based on the European Urban Audit 2018 (Eurostat, 2018), which reflect the Organisation for Economic Cooperation and Development (OECD) and European Commission's definition of cities (Fig. 1) (Dijkstra and Poelman, 2012).

2.2. Health impact assessment (HIA) methodology

We conducted a quantitative HIA at a 250m × 250m grid-cell level to estimate the impact of suboptimal exposure to green space and air pollution on natural-cause mortality for the European cities' adult inhabitants (aged ≥20 years). Green space was measured based on two

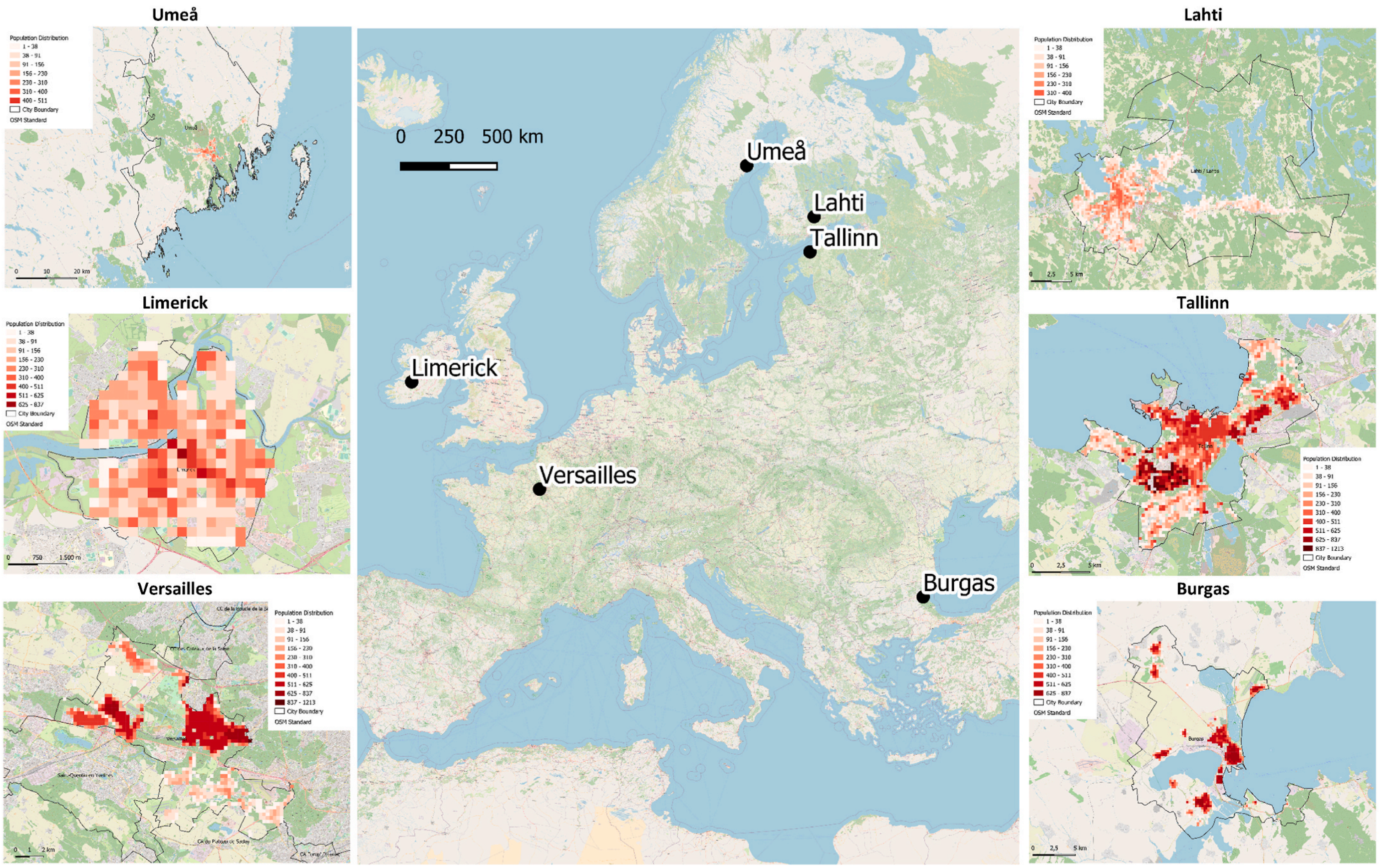

Fig. 1. Location of the studied cities, city boundary (based on Urban Audit) and population distribution.

proxies that have shown strong associations with mortality: normalized difference vegetation index (NDVI), and percentage of green area (% GA). NDVI usually represents general surrounding greenness (eg, street trees, gardens) while %GA usually represents publicly accessible green space (eg, parks, public squares) (Pereira Barboza et al., 2021). Air pollution concentrations were estimated for nitrogen dioxide (NO_2) and fine ambient particulate matter with a diameter less than or equal to 2.5 μm ($PM_{2.5}$).

We followed the comparative risk assessment approach, comparing the baseline situation to a counterfactual scenario (Murray et al., 2003) (Supplement 1). We defined our counterfactual scenario as compliance with the WHO recommendations for exposure to green space (WHO Regional Office for Europe, 2016) and air pollution (World Health Organization, 2021). Based on experts working group reports, WHO recommends that green spaces (of at least 0.5 ha) should be accessible within a 300 m linear distance of all residences (WHO Regional Office

Table 1
Counterfactual exposure level and exposure response functions per exposure.

Exposure	Counterfactual exposure level	Relative risk (95% CI)	Exposure	Health Outcome	Study design	Reference
Main analyses						
NDVI	Burgas = 0.467; Lahti = 0.501; Limerick = 0.605; Tallinn = 0.513; Umeå = 0.439; Versailles = 0.573	0.96 (0.94–0.97)	per 0.1 increase	All-cause mortality	Meta-analysis	Rojas-Rueda et al., 2019
%GA	25%	0.99 (0.98–1.00)	per 10% increase	All-cause mortality	Meta-analysis	Gascon et al., 2016
NO_2	10 μg/m^3	1.02 (1.01–1.04)	per 10 μg/m^3 increase	All-cause mortality	Meta-analysis	Huangfu and Atkinson, 2020
$PM_{2.5}$	5 μg/m^3	1.07 (1.03–1.11)	per 10 μg/m^3 increase	Natural-cause mortality	Meta-analysis	Chen and Hoek, 2020 (Europe)
Additional Analysis						
Noise	53 dB Lden	1.05 (0.97–1.13)	per 10 dB increase in Lden	IHD Mortality	Cohort	EEA (2020)
Sensitivity Analyses						
NDVI	Median NDVI	–	–	–	–	–
%GA	Median %GA	–	–	–	–	–
NO_2	–	1.02 (0.99–1.06)	per 10 μg/m^3 increase	All-cause mortality	Meta-analysis	Atkinson et al., 2018
NO_2	–	1.01 (0.99–1.03)	per 10 μg/m^3 increase	Natural-cause mortality	Meta-analysis	Beelen et al., 2014
$PM_{2.5}$	–	1.08 (1.06–1.09)	per 10 μg/m^3 increase	Natural-cause mortality	Meta-analysis	Chen and Hoek, 2020 (Worldwide)
$PM_{2.5}$	–	1.07 (1.04–1.09)	per 10 μg/m^3 increase	Natural-cause mortality	Meta-analysis	WHO, 2014
$PM_{2.5}$	–	1.07 (1.02–1.13)	per 5 μg/m^3 increase	Natural-cause mortality	Meta-analysis	Beelen et al., 2014

for Europe, 2016), suggesting NDVI and %GA as feasible measures for research purposes, however, without defining a specifically threshold. Hence, NDVI and %GA counterfactuals levels were defined based on previous studies that proposed translation of the WHO green space exposure recommendation into specific thresholds for both NDVI and %GA (Table 1) (Pereira Barboza et al., 2021; Khomenko et al., 2020; Mueller et al., 2017, 2018). Additionally, 2021 WHO guidelines for air pollution recommend that annual mean concentrations should not exceed 10 μg/m^3 for NO_2 and 5 μg/m^3 for $PM_{2.5}$ (Table 1) (World Health Organization, 2021). We retrieved exposure-response functions (ERF) from the literature, quantifying the strength of the association between mortality and exposure to green space and air pollution, independently (Rojas-Rueda et al., 2019; Gascon et al., 2016; Huangfu and Atkinson, 2020; Chen and Hoek, 2020) (Table 1). For each grid cell and age group, we estimated the baseline green space (i.e., NDVI and %GA) and air pollution (i.e., NO_2 and $PM_{2.5}$) exposure levels. We determined the exposure level difference between the baseline and the counterfactual levels and estimated the relative risk (RR) associated with the exposure level difference (based on the ERF). We calculated the population attributable fraction (PAF) and estimated the preventable mortality burden (based on the PAF and the natural-cause deaths). We estimated the results by grid cell and by city, as well as the preventable age-standardized mortality rate (ASMR) equivalent to deaths per 100, 000 persons, according to the European Standard Population (Eurostat, 2013), the percentage of preventable annual natural-cause deaths, and standardized years of life lost (YLL). Exposure assignment and data analysis were done using QGIS (version 3.16.5-Hannover), R (version 4.2.2), and Python (version 3.9.15).

2.3. Population and age distribution

The total number of inhabitants per grid cell was retrieved from the Global Human Settlement Layer (GHSL) for 2015 (European Commission, 2019) which was the latest available population layer with a similar resolution for the six cities (i.e., 250 m × 250 m). We reduced the baseline GHSL dataset to grid cells on residential areas, based on the European Urban Atlas 2012 (Copernicus, 2012). We re-distributed the population of the removed grid cells according to the population density of the remaining grid cells (Supplement 2). Given the variability of total and residential areas, the number of grid-cells in the final dataset varied in each city ($n_{Burgas} = 612$ in; $n_{Lahti} = 1641$; $n_{Limerick} = 266$; $n_{Tallinn} = 1425$; $n_{Umeå} = 2937$; and $n_{Versailles} = 655$). The population age distribution for 2015 was obtained from Eurostat at the Nomenclature of Territorial Units for Statistics (NUTS) 3 level (Eurostat, 2018; Eurostat, 2019). We retrieved population data by age group (i.e., aged ≥20 years, 5-year groupings) and calculated the population proportion per age group, assuming the same age distribution between the NUTS3-level and the corresponding city level.

2.4. Mortality counts

The total all-cause deaths by city were available for 2015 from Eurostat city statistics (Eurostat, 2019). We calculated the proportion of external deaths (following the Eurostat definition) by adult age group and discounted it from the all-cause mortality counts to compute the natural-cause deaths. We estimated the proportion of natural deaths by adult age group at the NUTS3-level and applied them to the city-level total all-cause mortality counts to estimate the number of natural deaths by adult age group, and, then, to the corresponding grid cells.

2.5. Baseline exposure levels

2.5.1. Green space

NDVI level was retrieved from Terra Moderate Resolution Imaging Spectroradiometer (MODIS) Vegetation Indices (MOD13Q1, US Geological Survey, from April 1 to June 30, 2015) (US. Geological Survey, 2021). Cloudy and snow or ice pixels were removed, and water bodies were masked out with MOD44W.005 data product. NDVI levels range between −1 and 1, with higher positive values indicating more greenness. To reflect the WHO recommendation of residential exposure to green spaces, we estimated the total averaged NDVI value by adding a 300-m buffer around each grid cell to indicate the proximity to greenness (i.e., 5 min walk along walkable pathways). We retrieved data for %GA from the European Urban Atlas 2012 (0.25-ha resolution) (Copernicus, 2012). For Lahti, for which the Urban Atlas was unavailable, %GA was retrieved from Corine Land Cover (2012) inventory (25-ha resolution) (Copernicus, 2012). Following the same approach as for NDVI, we estimated the total amount of %GA by adding a 300 m buffer around each grid cell (Supplement 3).

2.5.2. Air pollution

For Lahti, Limerick, Umeå, and Versailles, annual mean NO_2 and $PM_{2.5}$ concentration estimates were retrieved from land use regression (LUR) models (100 m × 100 m) developed for 2010 as part of the Effects of Low-Level Air Pollution: a Study in Europe (ELAPSE) project (de Hoogh et al., 2018). ELAPSE values were adjusted with temporal data for 2015 from the European air quality database (AirBase) to estimate baseline annual mean NO_2 and $PM_{2.5}$ concentrations at the grid-cell level for 2015. We followed this approach given that ELASPE values for 2010 were generally higher than Airbase values for 2015 (Khomenko et al., 2021b). For Burgas and Tallinn, for which the ELAPSE model estimates were unavailable, the annual mean $PM_{2.5}$ values were extracted from the Ensemble model (10 km × 10 km) (Copernicus, 2019) for 2015. Annual mean NO_2 estimates were retrieved from the Global LUR model (100 m × 100 m) for NO_2 for 2011, given a higher resolution in comparison to Ensemble model that allowed us to consider relevant NO_2 spatial variation within each city. We followed the same approach as a previous study (Khomenko et al., 2021b), in which Global LUR NO_2 values were comparable to Airbase 2015 values. Hence, we assumed Global LUR NO_2 values as representative for 2015.

2.6. Socioenvironmental inequalities

To evaluate potential inequalities in exposure and mortality according to the population's socioeconomic status in each city, we used the average household annual income as a proxy. This data was available for Lahti, Limerick, Tallinn, Umeå, and Versailles at different spatial levels (i.e., regions, subdistricts, grid cells) (see Supplement 4 for further details) (Statistics Finland, 2015; Central Statistics Office, 2019; Tallinn City Council, 2019; Open Data Umea, 2016; INSEE, 2017). For Versailles, income data was not available, so we utilized data on 'standard of living' (*niveau de vie*), defined as the income per consumption unit (INSEE, 2017). We did not assess potential inequalities in exposure and mortality for Burgas, since socioeconomic data were only available at the city level.

We estimated the average household annual income per grid by applying the area-weighted mean assignment. Given the range of income differs from each city and that purchasing power might vary across countries, we calculated the quintile distribution of income levels for each city separately and assigned the quintile numbers to the grid cells accordingly (i.e., quintile 1 representing the lowest income levels and quintile 5 representing the highest income levels). We stratified our analysis according to the income quintiles and estimated the attributable mortality impacts by income. We carried out ANOVA and Tukey Honestly Significant Difference tests to verify the statistical significance of the association between the income quintiles and environmental exposure levels, as well as income quintiles and percentage mortality impacts, and compared groups of different incomes to check whether adverse environmental exposure levels were more prevalent based on income distribution in each city (Supplement 4).

In sequence, we applied cluster spatial correlation from Bivariate Moran's I (Anselin, 1995), in order to spatially identify the association between the average annual income levels and the impact on mortality due to environmental exposures (i.e., NDVI, %GA, NO_2, and $PM_{2.5}$). The bivariate analysis allows us to inspect the relationship between two variables and their spatial position. In particular, it describes the correlation between the non-lagged dependent variable (i.e., income) with the spatially lagged dependent variables (i.e., percentage of impact on natural-cause mortality due to each environmental exposure) (Anselin, 1995). A cluster is defined when the value of a first variable (i.e., high or low) in an area is more associated to the value of the spatially lagged second variable at the neighboring areas than when there is spatial randomness (considering a 95% significance level). Then, spatial clusters are defined as areas with "high income-high mortality impact" or "low income-low mortality impact" (i.e., high-high or low-low), representing positive local spatial autocorrelation. In contrast, spatial outliers are defined as areas with "high income-low mortality impact" or "low income-high mortality impact" (i.e., high-low or low-high), representing negative local spatial autocorrelation (Supplement 4).

2.7. Economic analysis

The economic analysis was performed by using the Value of Statistical Life (VSL) and the Value of Life Years Lost (VOLY) approaches, which represents the societal economic value of the reduced risk of premature mortality. For VSL, the OECD reference value for high-income countries was adjusted according to income differences across the countries by the World Bank. We considered the VSL for 2015 of €2.891 million for all six cities, since they are included in the EU27 countries list (World Health Organization, 2017). Economic impacts were calculated by multiplying the VSL by the estimated attributable deaths due to non-compliance with exposure levels recommendations in each city. For VOLY, the adjusted impacts are based on the mortality by age distribution. We considered VOLY for 2015/2016 of €70,000 from CE Delft reference for European cities (de Bruyn and de Vries, 2020; De Bruyn et al., 2018). Economic impacts were calculated by multiplying the VOLY by the standardized YLL due to non-compliance with exposure levels recommendations in each city.

2.8. Additional and sensitivity analyses

We performed additional analysis to estimate the impact of road traffic noise on ischemic heart disease mortality. Road traffic noise levels were retrieved from strategic noise maps by END (European Environmental Agency, 2023), using the 24-h day-evening-night noise level indicator (Lden). Data were available for Lahti, Tallinn, and Versailles. We estimated road traffic noise (i.e., Lden) exposure levels for each grid cell and calculated the population distribution in 5-dB noise bands. We set the counterfactual scenario to 53 dB Lden, based on WHO recommendation (WHO Regional Office for Europe, 2018). We used ERF from the Environmental European Agency that states an increased risk estimate of ischemic heart disease mortality of 1.05 (95%CI: 0.97; 1.13) per each increase in 10 dB Lden noise exposure (European Environment Agency, 2020).

Finally, we applied sensitivity analyses considering the analysis based on the city level instead of the grid-cell level for all exposures. For green space, we also applied sensitivity analyses using the median city NDVI level and %GA as counterfactual scenarios to consider differences in NDVI and %GA within each city. For air pollution, we applied sensitivity analyses to estimate how our outcomes vary based on the use of different ERF (Chen and Hoek, 2020; Atkinson et al., 2018; Beelen et al., 2014; World Health Organization, 2014) (Table 1, Supplement 5).

3. Results

Overall, 804,975 adults lived in the six cities in 2015 (ranging from 33,917 adults in Limerick to 308,273 adults in Tallinn). The natural-cause mortality in 2015 was 9438 death counts (1172 deaths/100,000 persons-year; ranging from 282 deaths in Limerick to 3848 deaths in Tallinn) (Table 2).

Most cities showed mean levels of green space (i.e. NDVI and %GA; with exception of Limerick) greater than the WHO guidelines and recommendations (i.e., our counterfactuals) at a city level, with a high level of variability within the cities (Table 2). In fact, around 60% of the population lacked green space and 90% of the population were exposed to air pollution above the counterfactuals. For the NDVI proxy, we estimated an average of 0.537 and a mean range of 0.540. For the %GA proxy, we estimated an average of 40% and a mean range of 93%, with grid cells having no green space at all, while others were almost fully covered by green spaces in all cities (Table 2). Air pollution concentrations (i.e. NO_2 and $PM_{2.5}$) were higher than the WHO guidelines at city level, however, lower than the average of European cities (i.e., mean of 22.6 μg/m^3 for NO_2 and 13 μg/m^3 for $PM_{2.5}$) (Khomenko et al., 2021a, 2021b). For NO_2, we found a mean concentration of 16 μg/m^3 and a high variability, with a mean range of 26 μg/m^3. For $PM_{2.5}$, we found a mean concentration of 8 μg/m^3 and a low variability, with a mean range of 3 μg/m^3 (Table 2). The high level of variability found for NDVI, %GA and NO_2 suggests an unequal distribution of environmental exposures within the cities' territory (Fig. 2, Supplement 4). At the grid-cell level, air pollution was positively correlated with population, while green space was negatively correlated with air pollution and population (Supplement 3).

For NDVI, we estimated that summed across all six cities, 222 (95% CI: 166; 331) deaths might be attributable to NDVI below the counterfactual level (i.e., representing 28 deaths/100,000 persons, 2.4% of total mortality, and a mean of 241 standardized YLL/100,000 persons). The highest impact was in Burgas (i.e. attributable ASMR of 92 deaths/100,000 persons and 841 standardized YLL/100,000 persons), followed by Tallinn (i.e. attributable ASMR of 82 deaths/100,000 persons and 838 standardized YLL/100,000 persons), where 67% and 71% of the population was living in areas with sub-optimal greenness (i.e., NDVI below the target), respectively (Table 3).

For %GA, we estimated that in total, 76 (95%CI: 0; 151) deaths might be attributable to %GA not achieving 25% of the grid-cell area (i.e., representing 9 deaths/100,000 persons, 0.8% of total mortality and a mean of 80 standardized YLL/100,000 persons). The highest impact was in Burgas (i.e. attributable ASMR of 38 deaths/100,000 persons and 350 standardized YLL/100,000 persons), followed by Tallinn (i.e. attributable ASMR of 28 deaths/100,000 persons and 282 standardized YLL/100,000 persons), where 65% and 67% of the population was living in areas with less than 25%GA, respectively (Table 3).

For NO_2, we estimated that overall, 196 (95%CI: 100; 383) deaths were attributable to NO_2 concentrations above 10 μg/m^3, representing 24 deaths/100,000 persons. The highest impact was in Tallinn (i.e., attributable ASMR of 88 deaths/100,000 persons and 890 standardized YLL/100,000 persons), followed by Versailles (i.e., attributable ASMR of 79 deaths/100,000 persons and 848 standardized YLL/100,000 persons), where 100% of the population was living in areas with NO_2 levels above the WHO recommendation (Table 3).

For $PM_{2.5}$, we estimated that 219 (95%CI: 128; 278) deaths were attributable to $PM_{2.5}$ concentrations above 5 μg/m^3, representing 27 deaths/100,000 persons. The highest impact was in Burgas (i.e. attributable ASMR of 206 deaths/100,000 persons and 1884 standardized YLL/100,000 persons), followed by Versailles (i.e. attributable ASMR of 106 deaths/100,000 persons and 1131 standardized YLL/100,000 persons), where 100% of the population was living in areas with $PM_{2.5}$ levels above the WHO recommendation (Table 3).

3.1. Socio-environmental inequalities

We found that overall environmental exposures were correlated with the average annual income, with strongest relationships in Umeå and Versailles (Supplement 4). In terms of this relationship, we found two different patterns across the cities depending on where the more

Table 2
Baseline descriptive (2015 reference).

City	Area	Adult population	Adult natural-cause deaths	Domain	Data Source	Baseline exposure level				Counterfactual exposure level	% population in suboptimal grids
						Mean	Median	Min	Max		
Burgas, Bulgaria	255.4 km^2	136,990 (536 $inhab/km^2$)	1896	Green space (NDVI)	MODIS	0.478	0.481	0.224	0.758	0.467 (95% CI: 0.455; 0.479)	66.7
				Green space (%GA)	Urban Atlas	42.32	42.65	0.00	95.3	25%	64.6
				NO_2 air pollution	Global LUR	14.05	13.16	5.64	30.08	10 $\mu g/m^3$	93.4
				$PM_{2.5}$ air pollution	Ensemble	12.66	12.95	11.95	12.95	5 $\mu g/m^3$	100
Lahti, Finland	517.3 km^2	96,864 (187 $inhab/km^2$)	1175	Green space (NDVI)	MODIS	0.529	0.540	0.222	0.698	0.501 (95%CI: 0.492; 0.510)	52.2
				Green space (%GA)	Urban Atlas	43.65	43.8	0.00	100	25%	32.4
				NO_2 air pollution	Elapse	11.28	11.51	3.99	21.66	10 $\mu g/m^3$	79.2
				$PM_{2.5}$ air pollution	Elapse	5.65	5.87	3.76	6.98	5 $\mu g/m^3$	91.9
Limerick, Ireland	19.5 km^2	33,917 (1739 $inhab/km^2$)	282	Green space (NDVI)	MODIS	0.576	0.233	0.233	0.785	0.605 (95%CI: 0.586; 0.624)	71.2
				Green space (%GA)	Urban Atlas	23.74	20.2	0.88	74.6	25%	71.6
				NO_2 air pollution	Elapse	14.09	14.08	9.03	22.55	10 $\mu g/m^3$	97.3
				$PM_{2.5}$ air pollution	Elapse	5.65	5.87	3.76	6.98	5 $\mu g/m^3$	100
Tallinn, Estonia	159.5 km^2	308,273 (1933 $inhab/km^2$)	3848	Green space (NDVI)	MODIS	0.513	0.525	0.181	0.742	0.513 (95%CI: 0.506; 0.519)	70.8
				Green space (%GA)	Urban Atlas	28.8	24.6	0.00	91	25%	67.1
				NO_2 air pollution	Global LUR	22.45	22.56	11.28	48.88	10 $\mu g/m^3$	100
				$PM_{2.5}$ air pollution	Ensemble	6.63	6.81	5.84	6.88	5 $\mu g/m^3$	100
Umeå, Sweden	2396.2 km^2	136,344 (57 $inhab/km^2$)	1112	Green space (NDVI)	MODIS	0.529	0.549	0.194	0.795	0.439 (95%CI: 0.428; 0.449)	48.0
				Green space (%GA)	Urban Atlas	63.02	69	0.00	97.3	25%	38.9
				NO_2 air pollution	Elapse	6.76	6.15	1.09	23.2	10 $\mu g/m^3$	41.2
				$PM_{2.5}$ air pollution	Elapse	4.43	4.51	2.22	6.45	5 $\mu g/m^3$	61.5
Versailles, France	97.7 km^2	92,587 (948 $inhab/km^2$)	1125	Green space (NDVI)	MODIS	0.598	0.295	0.295	0.791	0.573 (95%CI: 0.564; 0.582)	65.8
				Green space (%GA)	Urban Atlas	38.47	37.6	0.00	97.7	25%	60.7
				NO_2 air pollution	Elapse	29.82	28.79	16.41	57.66	10 $\mu g/m^3$	100
				$PM_{2.5}$ air pollution	Elapse	13.8	13.7	11.93	15.56	5 $\mu g/m^3$	100

deprived populations live.

On the one hand, in Lahti, Tallinn, and Umeå, the areas of lower income levels tended to have lower exposure to green spaces (i.e., NDVI, %GA), higher exposure to air pollution (i.e., NO_2 and $PM_{2.5}$) (Fig. 2), and higher attributable mortality impacts in comparison to areas with higher income levels. In these cities, areas with lower income levels were mainly located in the city center, and areas closer to main roads with traffic and denser construction. Spatial bivariate correlation showed many areas of negative local spatial correlation (i.e., spatial outliers of "high income-low mortality impact" or "low income-high mortality impact"). Areas of higher mortality impacts were mainly located in the central areas for the three cities (i.e., Lahti, Tallinn, and Umeå), and spatially correlated with areas of high (i.e., positive clusters) and low (i.e., outliers) income levels. For Lahti and Tallinn, high mortality impacts were also present in eastern areas (i.e., close to highways). Areas of "high income-lower mortality impact" (i.e., outliers) were mainly located in the city outskirts. There are only few areas of "low income-low mortality impact" (i.e., negative clusters) (Figs. 3 and 4, Supplement 4).

On the other hand, in Limerick and Versailles, areas with lower income levels tended to have higher exposure to green spaces (i.e., NDVI, %GA), lower exposure to air pollution (NO_2 and $PM_{2.5}$) (Fig. 2), and lower mortality impacts in comparison to areas with higher income levels. In Limerick, areas with lower income levels were mainly located in the northern zone, while in Versailles they were mainly located in the city outskirts (i.e., north and south). Spatial bivariate correlation showed many areas of positive local spatial correlation (i.e., spatial clusters of "high income-high mortality impact" or "low income-low mortality impact"). Areas of "high income-high mortality impact" (i.e., positive clusters) were mainly located in the central areas in both cities, and for Versailles, also in areas close to a highway in the northern zone. Areas of lower mortality impacts were mainly located in the outskirts in both cities. In Versailles, there were only few areas of "high income-low mortality impact" or "low income-high mortality impact" (i.e., outliers) (Figs. 3 and 4, Supplement 4).

3.2. Economic analysis

In Lahti, Limerick, and Umeå, the environmental conditions in most of the city areas are close to WHO recommended levels, thus, generating low overall attributable mortality and economic impacts. We estimated an annual impact of 95 million 2015 € based on VSL *versus* 16 million 2015 € based on VOLY in Lathi, an annual impact of 43 million 2015 € based on VSL *versus* 40 million 2015 € based on VOLY in Limerick, and an annual impact of 61 million 2015 € based on VSL *versus* 8 million 2015 € based on VOLY in Umeå (Tables 2 and 3).

In contrast, most of the areas of Burgas, Tallinn, and Versailles showed suboptimal environmental conditions, with exposures not complying with WHO recommended levels, which generated high

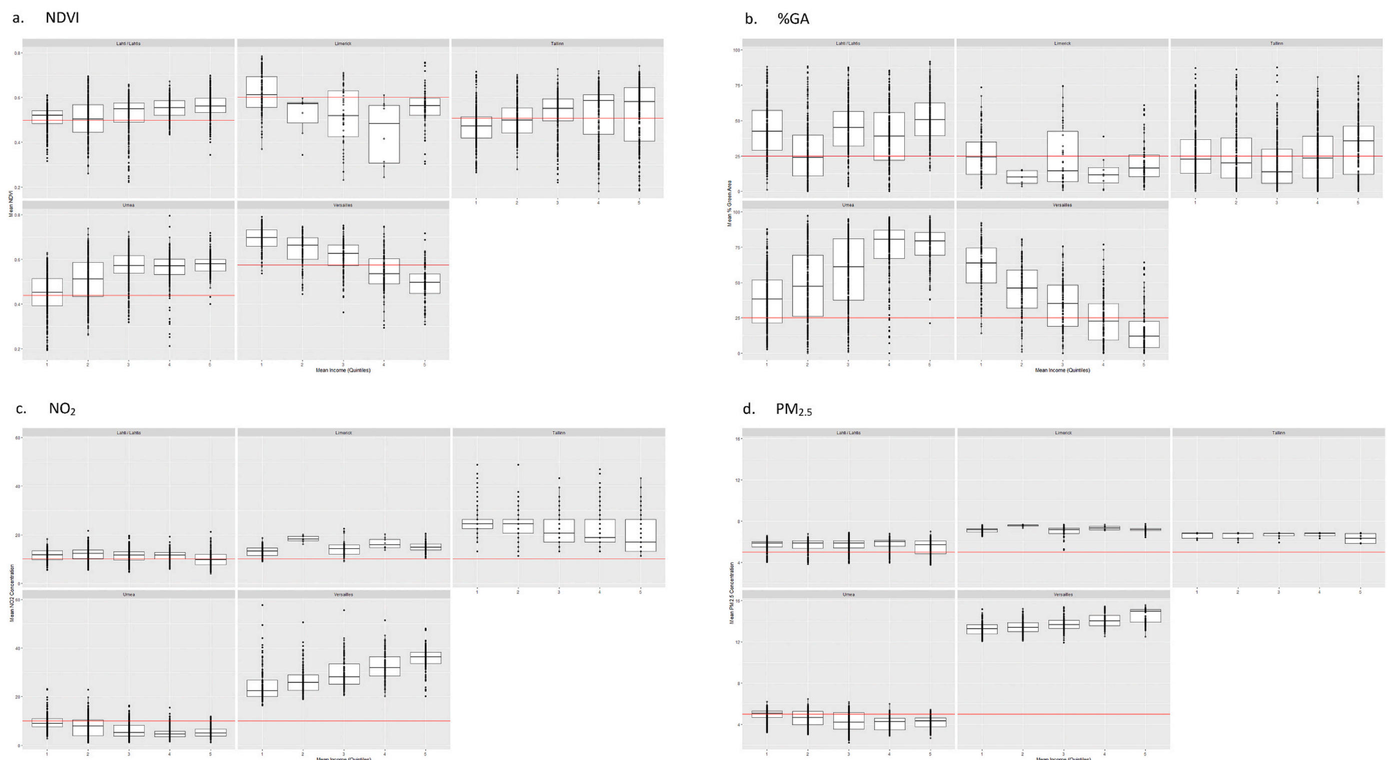

Fig. 2. Environmental Exposures Distribution by income quintiles per city (except Burgas).

overall attributable mortality and economic impacts. We estimated an annual impact of 466 million 2015 € based on VSL *versus* 171 million 2015 € based on VOLY in Burgas, 766 million 2015 € based on VSL *versus* 145 million 2015 € based on VOLY in Tallinn, and 413 million 2015 € based on VSL *versus* 169 million 2015 € based on VOLY in Versailles (Tables 2 and 3).

3.3. Additional and sensitivity analyses

We estimated 4 (95%CI: 0; 9) ischemic heart disease deaths attributable to noise levels above 53 dB Lden in Lahti, 16 (95%CI: 0; 38) in Tallinn, and 2 (0; 4) in Versailles, representing 0.2–0.4% of total deaths in each city (Supplement 5).

Applying the analysis at the city level instead of the grid-cell level resulted in reductions in the attributable mortality impact of all the cities (i.e., 63–100% reduction for NDVI, 67–100% reduction for %GA, and 14–100% reduction for NO_2 and 0–100% reduction for $PM_{2.5}$), indicating that accounting for the geographical distribution of exposures and population within the cities is important (Supplement 5).

For green space exposure, applying the median NDVI and %GA levels as alternative counterfactual scenarios for each city resulted in an increase in the attributable mortality impacts in Burgas (17% and 136% increase, respectively), Lahti (54% and 275% increase, respectively), and Umeå (188% and 658% increase, respectively), which suggests a high variability of green space levels within those cities. In contrast, for Limerick, the same scenario resulted in a reduction in the attributable mortality impact (100% and 38% reduction, respectively). Also, the attributable mortality presented reductions or increases depending on the proxy in Tallinn (12% increase for NDVI and 2% reduction for %GA) and Versailles (100% reduction for NDVI and 97% increase for %GA) (Supplement 5).

For air pollution exposure, using alternative ERFs, we identified the highest changes in the attributable mortality impacts with the use of the ERF from Beelen and colleagues (Beelen et al., 2014) (i.e., 39–57% reduction for NO_2 and 55–105% increase for $PM_{2.5}$), and similar results when using ERF from Atkinson and colleagues (Atkinson et al., 2018) (except for Limerick and Umeå) for NO_2 and WHO (2014) for $PM_{2.5}$ (Supplement 5).

4. Discussion

This HIA study estimated mortality impacts due to suboptimal environmental conditions (i.e., on green space and air pollution) and related socioenvironmental inequalities, being the first to focus specifically on medium-sized cities. In most of the cities, the populations were living in areas with insufficient exposure to green space (except Lahti and Umeå) and in almost all areas air pollution levels exceeded WHO recommended thresholds (except for Umeå). Overall, we estimated the largest mortality impacts to be attributed to low greenness levels in the cities (as measured by NDVI) (i.e., total of 222 (95%CI: 166; 331) deaths), followed by incompliant $PM_{2.5}$ concentrations (i.e., total 219 (95%CI: 128; 278) deaths), incompliant NO_2 concentrations (i.e., total 196 (95%CI: 100; 383) deaths) and, finally, insufficient %GA (i.e., total 76 (95%CI: 0; 151) deaths). This pattern was evident in Lahti, Limerick and Umeå. In Burgas and Versailles, $PM_{2.5}$ contributed to the largest mortality burden, followed by NDVI. In Tallinn, the second biggest contributor was NO_2, followed by $PM_{2.5}$. Inequalities in attributable mortality showed two different patterns and were dependent on whether low income populations lived in the more densely constructed, more trafficked and less green centric areas, or the less densely constructed, less trafficked and greener peripheric areas of the city.

Previous city-specific HIA studies that estimated the mortality impacts of the lack of green spaces and exposure to air pollution were conducted for larger European cities (i.e., +500,000 inhabitants). They were conducted for Athens, Barcelona, Bradford, Lisbon, London, Madrid, Paris, Stockholm, Turin, and Vienna (Iungman et al., 2021; Khomenko et al., 2020; Mueller et al., 2017, 2018; Kihal-Talantikite et al., 2019; Mitsakou et al., 2019). Most of these studies found that $PM_{2.5}$ was the largest contributor to premature mortality (i.e., 4–36 deaths/100,000 persons), while we found that for middle-sized

Table 3
HIA Outcomes (2015 reference).

City	Exposure domain	Annual preventable deaths (n) (95%CI)	Annual preventable mortality rate (deaths/100,000 inhabitants) (95%CI)	Annual preventable age-standardized mortality rate (deaths/100,000 inhabitants) (95% CI)	Years of Life Lost (YLL/100,000 inhabitants) (95%CI)	Standardized Years of Life Lost (YLL/100,000 inhabitants) (95%CI)	Annual preventable impact on deaths (%) (95%CI)	Annual economic impact in million 2015 € (95%CI) based on VSL	Annual economic impact in million 2015 € (95%CI) based on VOLY
Burgas	**NDVI**	43 (33; 65)	32 (24; 47)	92 (69; 137)	289 (217; 432)	841 (632; 1258)	2.28 (1.72; 3.42)	124.3 (95.4; 187.9)	58.9 (44.2; 88.1)
	%GA	18 (0; 36)	13 (0; 26)	38 (0; 76)	120 (0; 240)	350 (0; 697)	0.95 (0.00; 1.89)	52.0 (0.0; 104.1)	24.5 (0; 48.8)
	NO_2	21 (11; 42)	16 (8; 30)	45 (23; 89)	142 (72; 279)	413 (208; 810)	1.12 (0.57; 2.20)	60.7 (31.8; 121.4)	28.9 (14.6; 56.7)
	$PM_{2.5}$	97 (43; 147)	71 (31; 108)	206 (91; 313)	648 (287; 985)	1884 (835; 2865)	5.12 (2.27; 7.78)	280.4 (124.3; 425.0)	82.9 (58.5; 200.6)
								465.5 (251.5; 734.3)[a]	**170.7 (117.3; 345.3)**[a]
Lahti	**NDVI**	20 (15; 30)	21 (15; 31)	15 (11; 22)	198 (149; 297)	142 (107; 212)	1.69 (1.27; 2.53)	57.8 (43.4; 86.7)	9.9 (7.5; 14.8)
	%GA	4 (0; 8)	4 (0; 8)	3 (0; 6)	40 (0; 80)	29 (0; 58)	0.34 (0.00; 0.69)	11.6 (0.0; 23.1)	2.0 (0; 4.1)
	NO_2	6 (3; 12)	6 (3; 12)	4 (2; 9)	58 (29; 115)	42 (21; 83)	0.50 (0.25; 0.98)	17.3 (8.7; 34.7)	2.9 (1.5; 5.8)
	$PM_{2.5}$	7 (3; 10)	7 (3; 10)	5 (2; 7)	65 (29; 101)	47 (20; 72)	0.56 (0.24; 0.86)	20.2 (8.7; 28.9)	3.3 (1.4; 5.0)
								95.4 (60.7; 150.3)[a]	**16.2 (10.4; 25.7)**[a]
Limerick	**NDVI**	8 (6; 13)	25 (19; 37)	33 (25; 49)	243 (183; 361)	319 (240; 474)	2.99 (2.25; 4.44)	23.1 (17.3; 37.6)	22.3 (16.8; 33.2)
	%GA	3 (0; 5)	8 (0; 16)	11 (0; 21)	79 (0; 157)	104 (0; 207)	0.97 (0.00; 1.94)	8.7 (0.0; 14.5)	7.3 (0; 14.5)
	NO_2	3 (1; 5)	7 (4; 15)	10 (5; 19)	73 (37; 144)	96 (49; 189)	0.90 (0.45; 1.77)	8.7 (2.9; 14.5)	6.7 (3.4; 13.2)
	$PM_{2.5}$	4 (2; 6)	12 (5; 19)	16 (7; 25)	119 (52; 183)	157 (69; 241)	1.47 (0.64; 2.25)	11.6 (5.8; 17.3)	11.0 (4.8; 16.9)
								43.4 (26.0; 69.4)[a]	**40.0 (25.1; 63.3)**[a]
Tallinn	**NDVI**	108 (81; 161)	35 (26; 52)	82 (62; 123)	355 (267; 529)	838 (630; 1251)	2.79 (2.10; 4.17)	312.2 (233.8; 464.2)	58.7 (44.1; 87.6)
	%GA	36 (0; 72)	12 (0; 23)	28 (0; 55)	119 (0; 238)	282 (0; 562)	0.94 (0.00; 1.87)	104.1 (0.0; 208.2)	19.7 (0; 39.3)
	NO_2	114 (58; 222)	37 (19; 72)	88 (44; 171)	376 (191; 733)	890 (451; 1733)	2.97 (1.50; 5.78)	329.6 (167.7; 641.8)	62.3 (31.6; 121.3)
	$PM_{2.5}$	43 (19; 66)	14 (6; 22)	33 (15; 51)	143 (62; 219)	337 (148; 518)	1.12 (0.49; 1.73)	124.3 (54.9; 190.8)	23.6 (10.4; 36.3)
								766.1 (456.4; 1296.9)[a]	**144.6 (86.0; 245.1)**[a]
Umeå	**NDVI**	17 (12; 25)	18 (13; 27)	10 (8; 15)	158 (118; 236)	90 (67; 134)	1.47 (1.11; 2.21)	49.1 (34.7; 72.3)	6.3 (4.7; 9.4)
	%GA	5 (0; 10)	5 (0; 10)	3 (0; 6)	46 (0; 92)	26 (0; 52)	0.43 (0.00; 0.86)	14.5 (0.0; 28.9)	1.8 (0; 3.7)
	NO_2	2 (1; 5)	3 (1; 5)	1 (1; 3)	23 (12; 45)	13 (7; 26)	0.22 (0.11; 0.42)	5.8 (2.9; 14.5)	0.9 (0.5; 1.8)
	$PM_{2.5}$	2 (1; 2)	2 (1; 3)	1 (0; 1)	15 (6; 23)	8 (4; 13)	0.14 (0.06; 0.21)	5.8 (2.9; 5.8)	0.6 (0.3; 0.9)
								60.7 (40.5; 92.5)[a]	**7.8 (5.5; 12.1)**[a]
Versailles	**NDVI**	26 (19; 39)	19 (14; 28)	41 (31; 61)	202 (152; 302)	435 (327; 650)	2.32 (1.74; 3.47)	75.2 (54.9; 86.7)	30.5 (22.9; 45.5)
	%GA	10 (0; 20)	7 (0; 15)	16 (0; 31)	78 (0; 156)	168 (0; 335)	0.90 (0.00; 1.79)	28.9 (0.0; 57.8)	11.8 (0; 23.5)
	NO_2	50 (26; 97)	37 (19; 71)	79 (40; 154)	394 (200; 762)	848 (431; 1641)	4.52 (2.30; 8.74)	144.5 (75.2; 280.4)	59.4 (30.2; 114.9)
	$PM_{2.5}$	67 (30; 102)	49 (22; 75)	106 (47; 161)	525 (233; 796)	1131 (503; 1715)	6.03 (2.68; 9.14)	193.7 (86.7; 294.9)	79.2 (35.2; 120.1)

(*continued on next page*)

Table 3 (*continued*)

City	Exposure domain	Annual preventable deaths (n) (95%CI)	Annual preventable mortality rate (deaths/ 100,000 inhabitants) (95%CI)	Annual preventable age-standardized mortality rate (deaths/100,000 inhabitants) (95% CI)	Years of Life Lost (YLL/ 100,000 inhabitants) (95%CI)	Standardized Years of Life Lost (YLL/100,000 inhabitants) (95%CI)	Annual preventable impact on deaths (%) (95%CI)	Annual economic impact in million 2015 € (95%CI) based on VSL	Annual economic impact in million 2015 € (95%CI) based on VOLY
								413.4 (216.8; 662.0)[a]	**169.0 (88.3; 280.4)**[a]

NDVI = Normalized Difference Vegetation Index. %GA = percentage of green area. NO_2 = nitrogen dioxide. $PM_{2.5}$ = particulate matter with a diameter of 2.5 μm or less.

[a] Overall economic costs per city estimated considering NDVI, NO_2 and $PM_{2.5}$ economic outcomes. %GA outcomes were not included due to overlap with NDVI outcomes and that NDVI ERF is more robust.

European cities low NDVI exposure was associated with the highest mortality burden, followed by $PM_{2.5}$ concentrations. A large-scale HIA study focused on around 1000 European cities found that most of these larger cities had higher mortality impacts attributable to high $PM_{2.5}$ air pollution in comparison to the cities we analyzed, which can partially explain the lower impacts we found (Khomenko et al., 2021b). Additionally, in previous studies, green space exposure was estimated based on %GA proxy only and they found mortality impacts of 0–22 deaths/100,000 persons due to lack of %GA (Iungman et al., 2021; Khomenko et al., 2020; Mueller et al., 2017, 2018; Kihal-Talantikite et al., 2019; Mitsakou et al., 2019). We included NDVI and %GA as proxies for green space exposure and found that impacts based on %GA were lower than when using NDVI, similar to a previous study showing that attributable deaths based on %GA were half those for NDVI (Pereira Barboza et al., 2021). This is partially explained by the ERF used to associate NDVI with mortality (Rojas-Rueda et al., 2019) is more robust and shows stronger effects than the ERF associated with %GA and mortality (Gascon et al., 2016).

Regarding previous HIAs and air pollution impacts, different results can be observed, possibly due to the use of different counterfactuals. We considered the more restrictive 2021 WHO air pollution guidelines (World Health Organization, 2021), while other studies considered less restrictive 2005 WHO guidelines (World Health Organization, 2006). Moreover, previous HIA studies also estimated mortality impacts due to harmful noise and mainly found that less than 1% of total mortality in each city could be avoided by reducing noise levels to WHO guidelines (Iungman et al., 2021; Khomenko et al., 2020; Mueller et al., 2017, 2018; Kihal-Talantikite et al., 2019; Mitsakou et al., 2019), which is in line with our additional analysis for noise for Lahti, Tallinn, and Versailles, that resulted in mortality impact estimates ranging between 0.2 and 0.4% of the total mortality (i.e., lower impacts than for other exposures). We believe that some impact differences may also occur due to different units of analysis (i.e. grid cell *versus* census tracts, districts, neighborhoods, city levels) and years of data.

We followed a similar approach in terms of spatial unit, year of study, and green space (Pereira Barboza et al., 2021) and air pollution (Khomenko et al., 2021b) measures used in previous large-scale HIA studies for many European cities (Khomenko et al., 2022). While we found equivalent impact estimations for the six cities, none of these large-scale HIA other studies examined the socioeconomic spatial distribution of the outcomes. In comparison to the previous studies in European cities, others found that mortality impacts due to lack of green space accounted for 0.22%–5.52% of total natural-cause mortality (Khomenko et al., 2022), while our results varied between 1.47% and 2.99% of total natural-cause mortality. For %GA below WHO guidelines, others found impacts varying from 0.02% to 2.02% of total mortality (Khomenko et al., 2022), while our results varied within this range (i.e., between 0.34% and 0.97%). For air pollution, previous research reported that the impact varied from 0.0% to 0.6% of total mortality using the 2005 WHO NO_2 guidelines (European Environmental Agency, 2022), while we estimated a higher range (i.e., 0.50%–4.52%) of total mortality, given the updated 2021 WHO NO_2 guidelines (World Health Organization, 2021). For $PM_{2.5}$, others estimated an impact of 0–11% of total mortality based on 2005 WHO $PM_{2.5}$ guidelines (European Environmental Agency, 2022), while we estimated a range of 0.56%–6.03% of total mortality based on 2021 WHO $PM_{2.5}$ guidelines (World Health Organization, 2021).

4.1. Local aspects and attributable impacts

In general, the highest mortality impacts were found in Burgas, Tallinn, and Versailles, which are the cities with larger populations and/or greater population densities. The main impact on mortality in Burgas was due to high levels of $PM_{2.5}$, followed by low NDVI levels. Burgas center and southern areas are surrounded by two industrial areas and the port, besides having an airport in the northeast, potentially contributing to high $PM_{2.5}$ exposure (Barberi et al., 2021; Riley et al., 2021). Additionally, major roads and avenues are located near residential areas. In Burgas, the NDVI was highly correlated with %GA, suggesting that the city lacks surrounding vegetation besides official green areas (eg, low level of street vegetation).

In Tallinn, the main impact on mortality was due to high levels of NO_2, followed by low NDVI levels. Out of the six cities, Tallinn is the most populated and dense city, which is associated with high traffic density (World Health Organization, 2014). There are two of the main important roads in Estonia (heavily used by commuting traffic (Part, 2021)), the Tallinn airport in the east, and the Tallinn port in the north (important port in the Gulf of Finland located near dense residential areas), which are primary sources of air and noise pollution (Khomenko et al., 2023). For green spaces, Tallinn also lacks surrounding vegetation in areas outside official green areas, except in neighborhoods in the southwest.

In Versailles, despite having a relatively high amount of green spaces within the city, NO_2 and $PM_{2.5}$ levels were also quite high, contributing the most to mortality impacts. Despite not being highly populated, Versailles is quite dense, which was associated with high traffic density (World Health Organization, 2014). Therefore, in Versailles, the main air pollution-related mortality impacts were estimated in the city center and near the main road connecting to Paris. Moreover, the proximity to the French capital also contribute to high NO_2 and $PM_{2.5}$ concentrations (Khomenko et al., 2023).

Limerick is the smallest city in terms of area and population out of the six cities, however, it is one of the cities with the highest population density (i.e., 1739 inhabitants/km^2). Despite not having the highest impact on the number of deaths (i.e., given its population size), the percentage impact on total mortality for NDVI, %GA and NO_2 was similar to Burgas, Tallinn, and Versailles. The city is dense, which is associated with high traffic (World Health Organization, 2014), the main local contributor to high NO_2 concentrations (Khomenko et al., 2023). Moreover, as for Burgas and Tallinn, the NDVI and %GA were

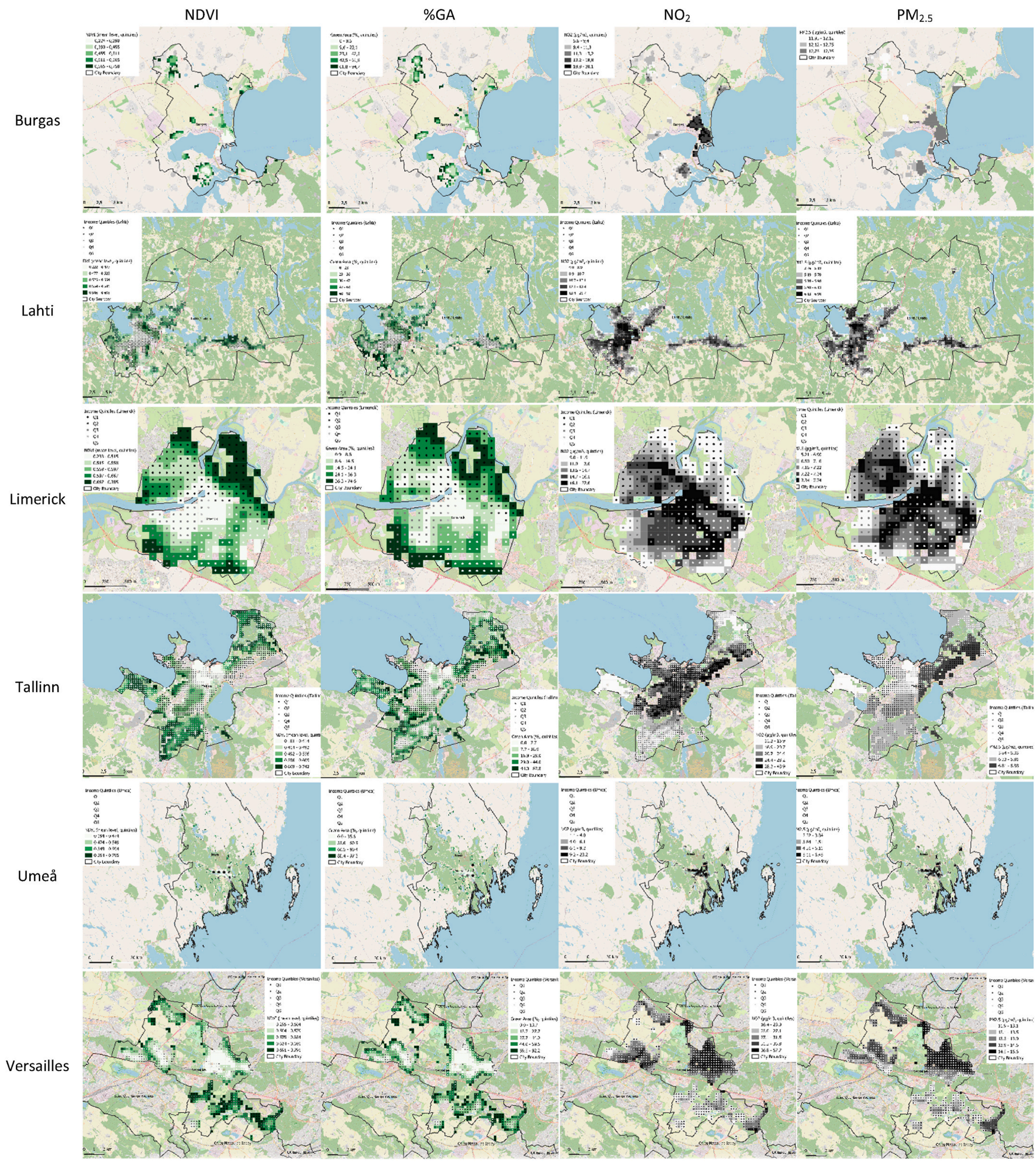

Fig. 3. Exposure (all cities) and income (except Burgas) distribution by quintiles per city.

highly correlated, indicating lack of surrounding greenness, except for the northwestern areas.

The lowest mortality impacts were found for Lahti and Umeå. Despite population size similar to the other cities, the population densities in Lahti and Umeå were pretty low, with less than 200 inhabitants per km^2. In Lahti, urban sprawl (i.e., phenomenon of population being fragmented distributed across the space (OECD, 2018)) follows two large highways that connects with the city center, generating a moderate air pollution-related mortality impact among areas adjacent to the major roads. In Umeå, urban sprawl is even more significant, with a high population dispersion in the large territory, and medium-density areas concentrated towards the city center, with lower green space and higher

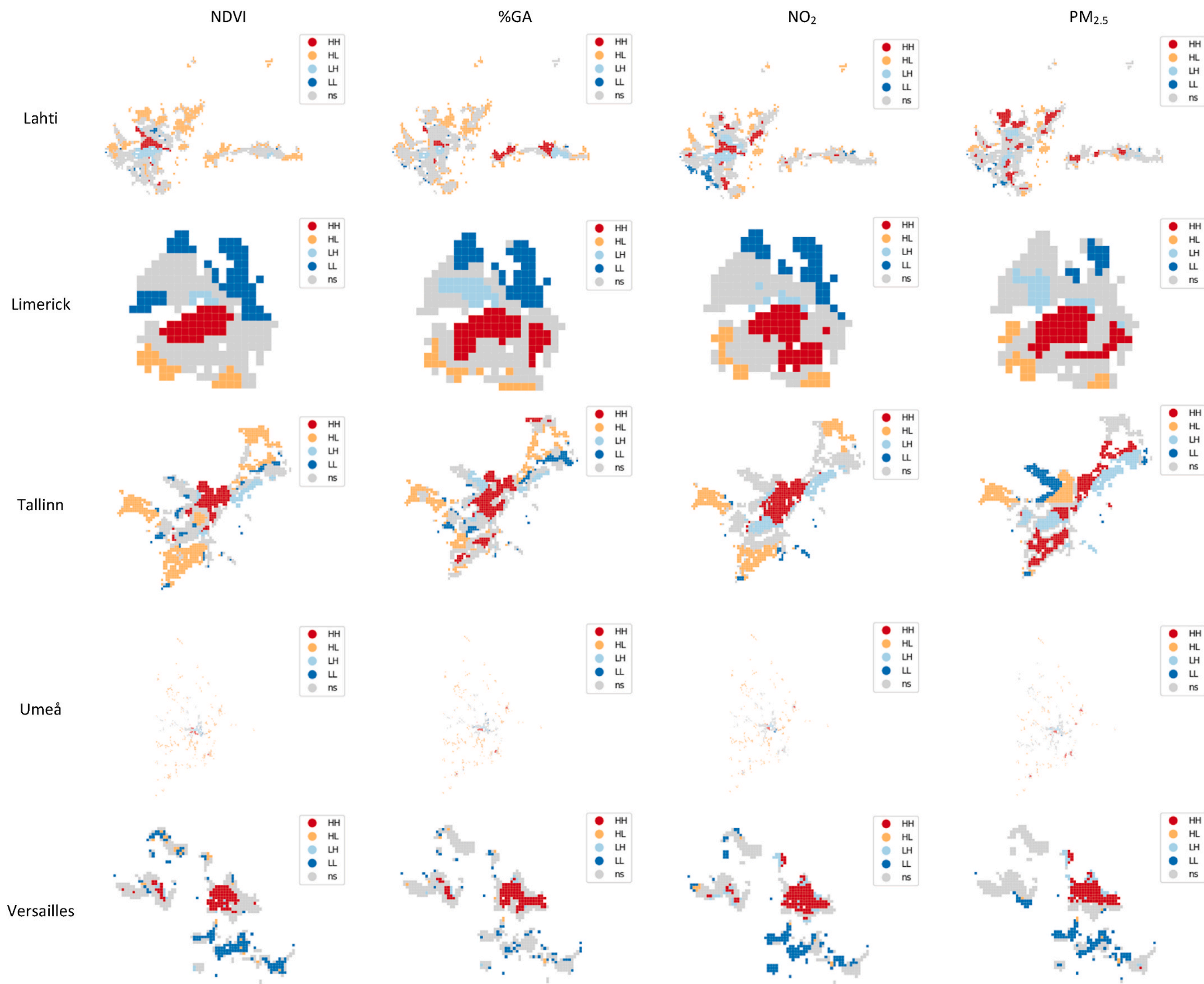

Fig. 4. Spatial correlation analysis (Bivariate Moran's I) for income and percentage impact on mortality by exposure per city
Spatial clusters (positive local spatial autocorrelation) are areas defined as "high-high" (high income-high impact) and "low-low" (low income-low impact), while spatial outliers (negative local spatial autocorrelation) are areas defined as "high-low" (high income-low impact) and "low-high" (low income-high impact).

air pollution.

The mortality impact estimations for Limerick, Lahti and Umeå are good examples of the competing trade-offs between the benefits of city density for sustainability purposes (i.e., low CO_2 emissions) *versus* the benefits of proximity to nature and lower air pollution or noise levels benefiting human health. Previous studies found associations between the increase in city density and the decrease in green space (McDonald et al., 2023) as well as increases in NO_2 air pollution (Borck and Schrauth, 2021). We also found that more densely populated grid-cells had higher air pollution and lower green space levels. However, evidence also indicates that denser cities with limited urban sprawl are associated with lower CO_2 emissions per capita, responsible for anthropogenic climate change intensification, and $PM_{2.5}$ per capita, responsible for important adverse health effects (Castells-Quintana et al., 2021; Gudipudi et al., 2016; European Environment Agency, 2023). Urban sprawl is also associated with fragmentation, increased infrastructure costs and inequalities (OECD, 2018). Specific local plans focusing on increasing green spaces and tackling air pollution in high-dense cities, as well as initiatives to reduce CO_2 emissions and possible inequalities in low-dense cities, should be prioritized to promote healthy environments while contributing to more sustainable urban settings.

4.2. *Average annual income and attributable impacts*

Overall, the high level of variability found for NDVI, %GA and NO_2 suggested an unequal distribution of environmental exposures (Fig. 3). We found two different patterns of socioenvironmental inequalities across the cities. In Lahti, Tallinn, and Umeå, the areas of lower income levels tended to have worse environmental conditions and higher mortality impacts in comparison to areas with higher income levels, similar to previous HIA studies for Barcelona, Bradford, Paris, and partially Vienna (Iungman et al., 2021; Khomenko et al., 2020; Mueller et al., 2018; Kihal-Talantikite et al., 2019). In these cities, populations with lower incomes tended to live in less favorable areas of the city, with heavy traffic and less green areas (i.e., central areas and close to highways), where the cost of living is probably cheaper. A recent study examining environmental inequalities in Oslo found that underprivileged districts were also more exposed to air pollution and heat, and were further from natural green-blue environments (Venter et al., 2023).

These conditions generate a "triple jeopardy" where socioeconomic deprivation is associated with harmful environmental conditions and increased risks to adverse health impacts due to material deprivation and psychosocial stress, which is in line with previous evidence (Kihal-Talantikite et al., 2019; Deguen and Zmirou-Navier, 2010; Verbeek, 2019).

On the other hand, in Limerick and Versailles, areas with lower income levels tended to have higher exposure to green spaces (i.e., NDVI, %GA), lower exposure to air pollution (NO_2 and $PM_{2.5}$), and lower mortality impacts in comparison to areas with higher income levels, partially similar to studies in Madrid (Iungman et al., 2021), Vienna (Khomenko et al., 2020) and Sao Paulo, Brazil (Pereira Barboza et al., 2022). In these cities, the more affluent populations live in areas near the city center, benefiting from proximity to work, services, and transportation (i.e., roads and train stations). As a result, they may be exposed to higher levels of pollution due to higher densities and more traffic. However, affluent populations have probably better resources to reduce their personal exposure to harmful environments (eg, with the use of air purification, climatization and ventilation in houses, etc.) and mitigate or restore adverse health impacts (eg, having better access to health services, better nutrition, etc.) (Verbeek, 2019). Hence, we expect the health burden of affluent populations to be lower than estimated, while socioeconomic deprived populations who live in the peripheral areas to be higher than estimated if they work or study in the city center.

4.3. Local policies and interventions for healthier environments

Our findings demonstrate that the six cities have different patterns of environmental conditions, mortality impacts, and associations with income levels. Moreover, we have shown that even cities with innovative urban green policies can have spatial and socio-inequalities when it comes to environmental and health conditions since exposure levels and mortality impacts varied by levels of income. Therefore, it is particularly important when defining urban policies to consider specific complexities of local context, besides recognizing differences and similarities between large and middle-sized cities.

To increase and promote green spaces' equal distribution and access, local policies should consider territorial dynamics. We have recognized that the higher mortality impacts due to the lack of NDVI or %GA were clustered in specific areas of each city. In those areas, targeted strategies could be applied given each situation. Possible initiatives are, for instance, the creation of new parks and pocket parks by regenerating degraded open areas (eg, inactive industrial zones), greater street greening by implementing green corridors, enhancement of overall vegetation in open public (grey) spaces, and stimulation of NBS in public and private built-up areas (eg, schools, hospitals, administrative and residential buildings). Those initiatives would also contribute to noise and air pollution reductions, temperature regulation and increasing biodiversity and climate-resilience (Nieuwenhuijsen, 2016; Iungman et al., 2023).

To reduce air pollution levels, policies focused on the main sources of air pollution are key. Given the role of transport as a major contributor for air pollution in all cities (Khomenko et al., 2023), strategies for healthier and more sustainable transport systems are needed, prioritizing active and public transportation, better connecting the city center with the peripheric and metropolitan areas with alternatives to reduce car-dependence. Most of these six cities lack safe and well-connected infrastructure to promote efficient, healthier and sustainable transport systems. Moreover, the daily commuting dynamics commonly goes beyond their boundaries (i.e., people commuting between different cities). In Tallinn, for instance, more than 60,000 people commuted to the city from outside daily in 2017 and most of the trips in the city are done by car (Part, 2021), which requests strategic actions at metropolitan or regional levels to improve access and connectivity to sustainable transport systems between cities. Additionally, other important sources of air pollution are domestic activities (eg, residential, commercial, institutional, i.e., Burgas, Lahti, Tallinn, Umeå, and Versailles), industrial activities (i.e., Burgas, Limerick, Tallinn, and Umeå) and port and shipping activities (i.e., Tallinn and Burgas) (Khomenko et al., 2023), for which integrated actions at different levels (i.e., national, subnational, metropolitan, etc.) are required to achieve more effective air pollution reductions.

Overall, we found that the annual economic mortality impact (in million 2015 €) based on VOLY estimations was considerably lower than those estimated based on VSL estimations (i.e., from 8% reduction in Limerick to 87% reduction in Umeå), which is in line with previous evidence (Chiabai et al., 2018; European Commission, 2022). In fact, the VOLY is the value of a single life year and consider the year of life lost for calculation, then, changing from city to city based on the population structure and mortality rates by age groups. The definition of a constant VOLY for all age-groups is criticized as for example that the value of a life year from a person of 30 years old could be less than for a person of 80 years old. Contrarily, the VSL is the monetary value of a whole life, being focused on preventing a fatality and assuming as same the value of each life lost, independently of the age. These discrepancies raise the question which is the better approach to value mortality, and how affects the discussion on local policies and interventions, given the differences in benefits-costs ratios based on VOLY or VSL (Chiabai et al., 2018).

4.4. Strengths and limitations

This is the first HIA study in medium sized cities that estimated the mortality impacts due to suboptimal exposures to green space and air pollution, the distribution thereof by the socioeconomic indicator of income. The fine grid-cell resolution (250m × 250m) allowed us to better understand and compare the spatial variations of each exposure, mortality impacts and income levels between and within the six cities. This level of disaggregation facilitates the orientation of evidence-based local policies.

There are some limitations associated with the study. Some challenges to perform an HIA in medium-sized cities was the lack of specific evidence quantifying associations between exposure and health in these urban contexts, as well as the lack of proper available data at fine resolution, particularly in terms of socioeconomic data (i.e., income), exposure assessment (eg, temporal adjustments and $PM_{2.5}$ data resolution of 10 km × 10 km for Burgas and Tallinn), and multiple health outcomes (eg, lack of morbidity data).

Income data was only available on different scales and different years for each city. We assumed that, even if values differ across years, the spatial distribution might not vary considerably, that the representation on quintiles distribution was suitable for the study. Our study points out the need for high quality and standardized registration of socioeconomic data across European cities. Socioeconomic data on high resolution can contribute to future studies looking specifically at socioenvironmental inequalities in urban contexts, identifying hotspots of environmental injustice. Additionally, standardized data collection procedures in terms of frequency, type of data, spatial resolution, etc. can contribute to providing better understanding of urban health processes and can help defined strategic policies aimed at urban justice, which is particularly important when considering increases in urban populations and migration processes in the near future.

Regarding the quantification of associations between environmental exposures and health, we used the same ERFs for all income groups. Nonetheless, the distinct underlying socioeconomic vulnerabilities across the population may differentially impact the link between exposures and health (Verbeek, 2019; Browning and Rigolon, 2018; Rigolon et al., 2021; Marselle et al., 2021). Unfortunately, we were not able to account for this, as available ERFs are not stratified by sociodemographic and socioeconomic factors. Better evidence on how associations between exposures and health might vary according to age, gender and socioeconomic factors are needed for future improvement of HIA studies. Additionally, we are aware that there are possible interactions and synergetic effects between the exposures included in this study (eg, modification of health effects of green spaces by air pollution). Therefore, we did not sum the estimated impacts by exposures to get a final total mortality burden by city, to avoid possible double counting. There is also emerging evidence exploring independent mortality effects of $PM_{2.5}$ and NO_2 still limited (World Health Organization, 2021), besides green space and air pollution.

It is worth noting that NDVI and %GA are both indicators of green space and vegetation. However, they do not reflect green space use or quality, which are important mediators of the effect of green space exposure on health (van Dillen et al., 2012; Knobel et al., 2021). Unfortunately, we lack proper data to conduct such analyses. Additionally, all cities (except for Versailles) exhibit considerable blue spaces (eg, sea, lakes, rivers), which might contribute to better health and reduction in the risk of mortality (Gascon et al., 2015; Van den Bosch and Sang, 2017). Blue spaces were not considered in this study due to the lack of standardized ERF needed for the HIA procedure. Hence, we believe that the overall mortality impacts estimated for cities could potentially be mitigated by the presence of blue spaces where green space levels were insufficient.

For air pollution, data from ELAPSE was not available for Eastern Europe, so we used $PM_{2.5}$ data from Ensemble for Burgas and Tallinn, with a resolution of 10 km × 10 km. Despite limited, we believe this is a reasonable proxy given the high dispersion capacity of PM and use in previous studies (Khomenko et al., 2021a, 2021b). Nevertheless, we point out the need to improve validated high-resolution models for air pollution for the whole of Europe, especially Eastern Europe, which can allow better and more comparable exposure assignation in further HIA studies. Additionally, we are aware that other air pollutants can also impact on health, e.g. short-term exposure to ozone (Orellano et al., 2020), however, we focused on $PM_{2.5}$ and NO_2, because of the association of long-term exposure with mortality and because $PM_{2.5}$ and NO_2 account for the largest proportion of health impacts of air pollution, according to the current evidence (European Environmental Agency, 2022).

Finally, exposure assignation was performed according to the population's place of residence. Real individual exposures and, in consequence, impacts due to suboptimal conditions might be influenced by how people move in the city territory and where people perform their daily activities. However, we followed the same approach as the ERFs, which are also based on residential exposure. Therefore, we believe the residential exposure as proxy to be appropriate in our analysis.

5. Conclusions

We attributed a considerable mortality burden to suboptimal exposure levels for green spaces and air pollution in Burgas, Lahti, Limerick, Tallinn, Umeå, and Versailles. Our findings demonstrate that even cities with innovative green policies can have unequal and unjust exposure level distributions and associated health impacts. NBS and urban greening in cities are good initiatives to provide appropriate environmental conditions and urban resilience in cities. However, the socioeconomic context needs to be considered and hotspots of health impacts need to be identified for targeted interventions in order to reduce inequalities.

Author contribution statement

Evelise Pereira Barboza: Conceptualization, Methodology, Software, Formal Analysis, Investigation, Data Curation, Writing – Original Draft, Writing – Review&Editing, Visualization. **Federica Montana**: Methodology, Software, Formal Analysis, Investigation, Writing – Review&Editing, Visualization. **Marta Cirach**: Software, Data Curation, Writing – Review&Editing. **Tamara Iungman**: Validation, Investigation, Writing – Review&Editing. **Sasha Khomenko**: Validation, Investigation, Writing – Review&Editing. **John Gallagher**: Validation, Investigation, Writing – Review&Editing. **Meelan Thondoo**: Validation, Investigation, Writing – Review&Editing. **Natalie Mueller**: Validation, Investigation, Writing – Review&Editing. **Hans Keune**: Investigation, Writing – Review&Editing. **Tadhg Macintyre**: Investigation, Writing – Review&Editing, Funding acquisition. **Mark Nieuwenhuijsen**: Conceptualization, Methodology, Supervision, Project administration, Writing – Review&Editing, Funding acquisition.

Data sharing

All the data collected is routinely collected data with no information on specific people. All the data is available upon request to the corresponding author (mark.nieuwenhuijsen@isglobal.org) and with agreement of the steering group.

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.

Data availability

Data will be made available on request.

Acknowledgments

We acknowledge support from the GoGreenRoutes through the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 869764, the grant CEX2018-000806-S funded by MCIN/AEI/10.13039/501100011033, and support from the Generalitat de Catalunya through the CERCA Program.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2023.116891.

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