Effect of tree canopy cover on air pollution-related mortality in European cities: an integrated approach

Pierre Sicard, Ionuț-Silviu Pascu, Stefan Petrea, Stefan Leca, Alessandra De Marco, Elena Paoletti, Evgenios Agathokleous, Vicent Calatayud

Summary

Background In urban areas, fine particles ($PM_{2·5}$), nitrogen dioxide (NO_2), and tropospheric ozone (O_3) are the most harmful air pollutants for human health. Urban greening is seen as a strategy for co-benefitting air quality, climate, and citizens' wellbeing. We aimed to estimate the changes in tree cover, the mortality burden attributable to air pollution, and the mortality that could be potentially prevented by increasing tree coverage in European cities.

Methods We did a quantitative health impact assessment to estimate the effect of mean tree cover on air pollutants levels and $PM_{2·5}$-related, NO_2-related, and O_3-related mortality (all ages) in 744 European urban centres, with more than 50 000 inhabitants, across 36 countries. We did all analyses at the city-wide scale.

Findings Between 2000 and 2019, the mean tree coverage increased by 0·76 percentage points, with 73·5% of the urban centres showing greener coverage, whereas mortality burdens declined by on average 3·39% (SD 0·28) in all urban centres. In 2019, about 25% of the total population lived in areas with a mean tree canopy coverage over 30%. Compared with the current tree cover, each five percentage point increase in tree canopy cover could facilitate an air quality improvement of 2·8% for annual $PM_{2·5}$ mean concentrations, 1·4% for annual NO_2 mean concentrations, and 1·2% for summertime mean of the daily maximum 8-h O_3 concentrations.

Interpretation We estimated that each five percentage point increase in tree canopy would potentially prevent 4727 premature deaths (95% CI 2067–7475) related to air pollution annually across the 744 European urban centres. We also estimated that reaching a canopy cover of 30% within each city could potentially prevent 11974 premature deaths (95% CI 7775–14 390) each year. Our results highlighted the potential public health benefits of increasing tree coverage in urban environments, contributing to sustainable, liveable, and healthier cities.

Funding LIFE financial instrument of the EU; Romanian National Research Authority; Agencia Estatal de Investigación, Ministerio de Ciencia e Innovación; Generalitat Valenciana; The European Regional Development Fund; and National Natural Science Foundation of China.

Lancet Planet Health 2025; 9: e527–37

ACRI-ST, Sophia-Antipolis, France (P Sicard PhD)**; INCDS, Voluntari, Romania** (P Sicard, I-S Pascu PhD, S Petrea PhD, S Leca PhD, A De Marco PhD)**; ENEA Casaccia Research Center, Rome, Italy** (A De Marco)**; IRET-CNR, Sesto Fiorentino, Italy** (Prof E Paoletti PhD)**; School of Ecology and Applied Meteorology, NUIST, Nanjing, China** (Prof E Agathokleous PhD)**; Fundación CEAM, Parque Tecnológico, Paterna, Spain** (V Calatayud PhD)

Correspondence to: Pierre Sicard, ACRI-ST, Sophia-Antipolis 06904, France **pierre.sicard@acri-st.fr**

Introduction

Ambient air pollution and global warming influence citizen wellbeing, human health, and biodiversity, particularly in cities.[1,2] In Europe (excluding Belarus, Russia, Türkiye, and Ukraine), about 73% of the population were living in urban centres (eg, cities, towns, and suburbs) in 2021, and this percentage could exceed 80% by 2050.[3] In cities, fine particles ($PM_{2·5}$), nitrogen dioxide (NO_2), and tropospheric ozone (O_3) pose a major threat to human health, natural ecosystems, and biodiversity.[2,4]

In European urban centres with more than 50 000 inhabitants, the annual mean NO_2 and $PM_{2·5}$ concentrations declined from 2000 to 2019 (on average –1·19% of annual mean NO_2 concentrations and –0·96% of $PM_{2·5}$ per year), with 99% of urban centres showing a decline of annual mean NO_2 concentrations and 93% of urban centres showing a decline of annual mean $PM_{2·5}$ concentrations.[4] The annual O_3 mean concentrations rose in 71% of the cities (on average 0·40% per year), whereas the summertime means of the daily maximum 8-h values (O_3 MDA8) declined in 62% of the urban centres by on average –0·29% per year.[4] In 2021, despite reductions in anthropogenic air pollutants emissions, over 90% of the European population were exposed to levels of $PM_{2·5}$, NO_2, and O_3 above WHO's air quality guidelines introduced in 2021 for human health protection, leading to half a million attributable deaths.[5] In addition, extreme heat events led to about 62 000 heat-related deaths in 35 European countries in the summer of 2022,[5] and urban heat islands increased mortality by 4% in the summer.[6]

Urban trees provide many benefits that enhance citizens' wellbeing, such as air pollution reduction, urban heat island mitigation, and biodiversity conservation.[7,8] In addition, urban trees can contribute to prevent premature deaths and reduce morbidity.[9,10] Therefore, efforts for optimising urban greenness for healthy cities are needed.[11] The EU launched the Biodiversity Strategy for 2030 to protect nature and biodiversity and asks European municipalities with at least 20 000 inhabitants to develop ambitious Urban Greening Plans. Following the EU recommendations, an intelligible guideline for

Research in context

Evidence before this study

We did a literature search in PubMed, Scopus, and Google Scholar from Jan 1, 1990, to Dec 30, 2024, and we found only a few relevant studies done in a small number of European cities. Only one study has investigated the effects of tree cover on preventable mortality burden due to air pollution for adult residents over 1 year at the city level. Until now, quantitative health impact assessments of the effect of mean tree cover on mortality were done for a fixed canopy cover of 30% within cities using green space proxies at coarse spatial resolution (250 m × 250 m). We also found a few studies in which the potential of urban green interventions to prevent mortality was estimated, but again these studies focused on extreme-heat events.

Added value of this study

To our knowledge, this is the first study to estimate the changes in tree cover, the mortality burden attributable to air pollution, and the mortality (all ages) that could potentially be prevented by increasing tree coverage in European cities. By using an integrated approach combining multiple datasets, our health impact assessment covered 744 European cities across 36 European countries over the past 20 years at a city-wide scale, and for the first time by considering trees that are 3 m or taller. We also estimated the number of deaths that could potentially be avoided for each five percentage point increase in tree canopy compared with 2019. Here, we provide novel evidence to inform future city-specific scenarios that could help mitigating harmful air pollution-related effects by protecting, restoring, and increasing tree canopy in cities.

Implications of all the available evidence

In urban environments, substantial mortality can be attributed to the effects of air pollution, and these effects could be lowered by increasing tree coverage. Green space planning, emissions control strategies, and other interventions can jointly improve public health. Although authorities have historically overseen managing public green spaces, citizens as major actors should be involved in the development and management of greening programmes to meet the recommended 30% tree canopy cover, by planting trees throughout private spaces. All the evidence will be valuable to policymakers for efficient policy implementation and healthier, sustainable and climate-resilient cities and human welfare in Europe and beyond.

urban greening (ie, the 3-30-300 rule) has been introduced in 2021.[12] Specifically, everyone would become able to see at least three trees from their home, school, or workplace; have more than 30% tree cover in their neighbourhood; and live within 300 m from a public green space.[12]

The view of greenery from home has been associated with better mental health, psychological restoration, and wellbeing, and fewer medications.[13] The access to greenery, within 300 m around a home, is associated with enhanced residents' wellbeing and reduced all-cause mortality.[14] Living in areas with over 30% canopy cover associates with reduced local air temperature, mitigated urban heat islands, prevented premature deaths, and lowered morbidity such as type 2 diabetes and cardiovascular diseases.[6,15,16] Increasing tree canopy cover to 30% could have prevented 2644 heat-related premature deaths (of people older than 20 years) across 93 European cities in the summer of 2015—ie, 1·84% of all summer deaths,[6] and 403 non-accidental deaths annually in Philadelphia, USA.[10]

The UN Economic Commission for Europe has recommended implementing the rule of 3-30-300, and many cities worldwide (eg, Barcelona, Seattle, Zurich) have the ambition to reach 30% of canopy cover through greening initiatives.[17] Despite the excitement around the 3-30-300 rule, much remains to be clarified and discussed.[18] In particular for the tree cover component, previous studies have done quantitative health impact assessments for a fixed canopy cover of 30%, while a more ambitious goal of 40% coverage has been suggested.[19] The population exposure was also estimated by using green space proxies—eg, the percentage of green area and the normalised difference vegetation index, at coarser spatial resolution (250 m by 250 m)—and only one study has investigated the effects of tree cover on preventable air pollution-related mortality for adult residents over 1 year at the city level.[20]

To date, better understanding of how urban tree cover is changing over time and the relationships between tree canopy cover and air pollution-related mortality are needed to decide whether current city management actions should change for the sustainability and citizen wellbeing in urban centres. Structural characteristics, such as tree canopy cover, are essential to quantify the benefits provided by urban trees.[11] On a city scale, tree attributes can be derived from airborne laser scanning, high-resolution imagery,[11] or sensors such as the Moderate Resolution Imaging Spectro-radiometer, MODIS, or LandSat.[21,22] The multi-decadal Landsat Analysis Ready Data is a unique open-source dataset (about 30 m per pixel) for quantifying changes in forest extent and height, cropland, and built-up lands from 2000 to 2020 in Europe.[23]

By using an integrated approach combining multiple datasets across Europe, we aimed to (1) estimate annual changes in tree canopy cover over the past 20 years across 744 European urban centres; (2) analyse the relationships between premature deaths related to $PM_{2·5}$, O_3, and NO_2 levels and percentage of tree cover; and (3) use this model to estimate the air pollution reduction that would result from increasing tree coverage to 30% for each city and estimate the number of deaths that could potentially be prevented as a result. Accordingly, we hypothesised that a 20-year time-series of data is considered long enough to detect short-term trends, likely due to emissions changes rather than meteorological variations, and that lower air pollution and related mortality are partly due to higher tree canopy cover in urban centres.

Methods

Urban centre boundaries and population datasets

As suggested by WHO, we categorised each grid cell as urban using the Global Human Settlement Layer Settlement Model (GHS-SMOD) and the high-resolution geospatial data on population distribution from WorldPop, both available at a 1×1 km of spatial resolution for all years from 2000 to 2019.[24] The GHS-SMOD dataset creates a globally harmonised definition of urban centres by measuring the degree of urbanisation, defined by density (≥1500 people per grid cell), continuity of grid cells, and total population ≥50 000. Therefore, the less densely populated areas are excluded. To enhance the accuracy of coastal urban boundary delineation, particularly in areas where urban development intersects with dynamic coastline features, we incorporated the Global Administrative Areas dataset.[25] Finally, 744 urban centres with more than 50 000 inhabitants were selected across 36 European countries (appendix pp 2–4). The urban centre boundaries can be different to administrative boundaries; however, the urban delineation does not significantly influence air pollutant concentration estimates.[26]

Air quality datasets

The year-specific ground-level annual $PM_{2·5}$ and NO_2 mean concentrations and summertime average of the daily 8-h maximum O_3 concentration (O_3 MDA8) were estimated at each 1 km² grid cell categorised as urban, then averaged over each urban centre for all years from 2000 to 2019 (appendix p 5).[27–29] The datasets of annual mean concentrations combine satellite-retrieved data, near-surface concentrations from global atmospheric chemical transport models, and ground-based measurements, and a geographically weighted regression is applied.[3] The estimated annual $PM_{2·5}$ (r^2 0·90–0·92), O_3 (r^2 0·81), and NO_2 (r^2 0·58) mean concentrations are well correlated to ground-based observations across Europe.[27–29]

Pollution-related premature mortality

To estimate air pollution-attributable mortality in the 744 urban centres, we applied the epidemiologically-derived health impact function established by WHO and widely used worldwide.[27–29] The population attributable fraction (PAF), which represents the proportion of disease burden that would be eliminated if the risk factor were reduced to the counterfactual pollutant concentration has been calculated at the grid-cell level:[27–29]

$$\text{PAF}=\frac{\sum[(RR_{c,h}-1)\times P_i]}{\sum[RR_{c,h}\times P_i]}$$

where RRc,h is the relative risk (simulated with a log-linear function of the difference between the concentration and the cutoff) derived from WHO's meta-analysis relative risk (reported per 10 μg m^{-3} increase) for the mortality endpoint (*h*) and air pollutant (*c*), P_i reflects the population exposed in the urban centre (*i*) extracted from WorldPop.

We then estimated $PM_{2·5}$-attributable, O_3-attributable, and NO_2-attributable mortality within each 1 km grid cell using the following equation:

For more on **geospatial data on population distribution** see https://www.worldpop.org/

$$N_{c,h,i}=BI_{h,i}\times P_i\times \text{PAF}$$

where $N_{c,h,i}$ is the mortality burden, $BI_{h,i}$ is the baseline mortality within the population of interest for the mortality endpoint (*h*) and urban centre (*i*) and P_i is the population exposed in the urban centre (*i*) extracted from WorldPop.

The annual country-specific baseline incidence rates (per 100 000 inhabitants) were obtained from the Global Burden of Diseases.[30] Epidemiological studies indicate that O_3 MDA8 during the summertime is significantly associated with natural mortality.[31] Based on WHO recommendations, we used relative risk estimates for non-accidental mortality (all ages) for European regions (appendix pp 6–7).[32–35] Subsequently, the annual $PM_{2·5}$-attributable, O_3-attributable, and NO_2-attributable deaths in each grid cell were summed according to geographical extents for all years from 2000 to 2019.

See **Online** for appendix

Tree canopy cover

The Landsat-derived Tree Canopy Height Change in Europe's dataset, developed by the Global Land Analysis and Discovery laboratory, is a yearly product providing estimates of tree canopy height at about 30 m of spatial resolution per pixel globally (appendix p 8).[36] We also integrated a subset of the Global Forest Canopy Height datasets from 2000 to cover the whole study period (ie, 2000–19).[22] We thus mapped the height of woody vegetation from 2000 to 2019 using the approach of Potapov and colleagues.[36] As recommended by Browning and colleagues,[18] each pixel showing canopy heights equal to or exceeding 3 m were classified as forested. The tree canopy extent dataset offers invaluable insights for estimating tree cover changes or exploring the drivers of tree canopy loss in cities.[23,36,37] Subsequently, all 30 m pixel estimates were summed according to geographical extents of each urban centre, providing insights into the presence and extent of the mean tree canopy cover within each urban centre. This approach allowed us a robust analysis of tree canopy cover across various cities, by handling spatial data, performing precise extractions, calculating tree cover percentages within each urban centre, and capturing year-to-year changes. To effectively analyse changes in urban tree canopy cover from 2000 to 2019, we employed a comprehensive data processing workflow using R Core Team.

Statistical analyses

Air quality, tree canopy cover, and mortality datasets were estimated within the same urban centre boundaries. We performed analyses at the city-wide scale. From year to year, the number of urban centres did not change. The non-parametric Mann-Kendall test and Sen's slope estimator were applied to the yearly tree canopy cover and the non-accidental mortality rates across 744 European urban centres from 2000 to 2019. For each country, a country-averaged trend magnitude was also calculated (in percentage per year) by joining all trends calculated for each urban centre (with $p<0·05$). Trend analyses were carried out with Openair package in R.

We estimated the effect of urban tree coverage on $PM_{2·5}$ and NO_2 mean concentrations and summertime O_3 MDA8 by running a linear mixed-effects model with package lm4 in R (appendix pp 9–10).[38] To account for the intrinsic differences in air pollution among cities (eg, different baseline pollutant levels due to differences in population, number of vehicles, or climatic conditions) and among years (eg, progressive reductions of primary pollutants due to the emissions control strategies), as well as interannual oscillations in the tree cover percentage (eg, urban development), both the city and the year were considered as random effects in the model, whereas the variable of interest, the tree cover, was the fixed effect. Based on the Akaike Information Criterion, the retained linear mixed-effects model can empirically extract the effect of tree cover with $p<0·001$ and a large portion of variance (r^2 >85%) is explained by the model.

We also estimated the number of deaths that could potentially be prevented by increasing tree coverage to 30% for each urban centre, and for each five percentage point increase in tree canopy compared with 2019. For cities with a current tree coverage of 30% or more (eg, in Finland), the actual value was considered as neutral change in the model. The term percentage point is used when comparing two different percentages; for example, if a tree cover increased from 10% to 15%, it has increased by five percentage points.

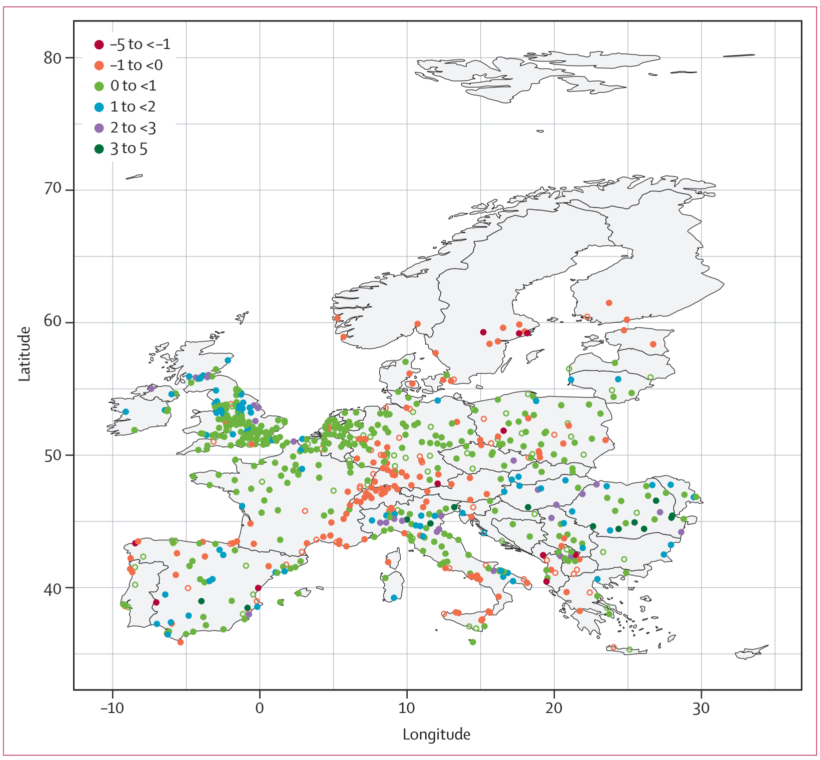

Figure 1: **Slope of the trends of yearly tree canopy cover (in percentage per year) per city from 2000 to 2019**
Closed circles represent significant trends ($p<0·05$) and open circles represent non-significant trends ($p>0·05$).

Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

Across the 36 European countries, the urban tree canopy coverage ranged from on average 2·5% in Malta to 36·3% in Finland from 2000 to 2019 (appendix pp 11–12). The mean urban tree coverage was 18·5% (SD 12·2) across the 36 European countries, and 18·9% (SD 12·1) across the 28 countries in the EU over 2000–19. In 2019, across the 744 European urban centres, 52 156 039 people (24·9%) of 209 706 939 (ie, the total population) lived in areas with a yearly mean tree canopy coverage of over 30% (130 urban centres). For the yearly tree canopy cover, the magnitude of trends between 2000 and 2019 varied widely among regions (figure 1). Across the 36 European countries, tree coverage increased by on average 0·22% per year in urban centres between 2000 and 2019 (ie, 0·76 percentage points over the study period), with 73·5% of the urban centres showing greener coverage. The proportion of urban tree coverage increased by on average 0·24% per year in the 28 countries in the EU (EU-28), (ie, 0·83 percentage points over the study period), with 75·9% of the urban centres showing an increase (appendix p 13).

For the whole of Europe, higher tree cover is significantly ($p<0·001$) associated with lowered $PM_{2·5}$ and NO_2 mean concentrations and summertime O_3 MDA8 (figure 2). For O_3, the summertime O_3 MDA8 could be reduced by 7·41% (SD 0·01) for a mean city tree coverage of 30% (41·21 [SD 0·35] parts per billion) compared with a hypothetical no tree scenario (44·51 [SD 0·43] parts per billion). Increasing mean city tree cover from 0% to

30% would reduce the $PM_{2·5}$ and NO_2 mean concentrations by 16·67% (SD 0·03) and 8·35% (0·04%), respectively (figure 2). Overall, we estimated that each five percentage point increase in tree canopy cover would reduce the summertime O_3 MDA8 concentrations by 1·2%, annual $PM_{2·5}$ mean concentrations by 2·8%, and annual NO_2 mean concentrations by 1·4% in large European urban centres.

Across the 36 European countries, the highest number of non-accidental $PM_{2·5}$-attributable, O_3-attributable, and NO_2-attributable deaths were found in eastern and southern Europe, particularly in several countries in southeastern Europe (ie, Bosnia and Herzegovina, North Macedonia, Serbia, Montenegro, and Kosovo; about 300 per 100 000 people), and the lowest rates were observed in northern Europe (about 20 per 100 000 people) from 2000 to 2019 (appendix pp 14–15). The highest attributable proportion of total deaths due to air pollution (appendix pp 16–17) was observed in Poland (17·4% [SD 3·4]) and Czech Republic (17·0% [3·8]), whereas the lowest proportion was found in Ireland (3·9% [2·2]) and Norway (5·5% [2·7]).

Per year, the mortality rates attributed to air pollution decreased by on average 3·39% (SD 0·28) in the 36 European countries and 3·54% (0·27) in EU-28. Between 2000 and 2019, the estimated number of premature deaths attributed to air pollution decreased in all European urban centres with a strong decline (about –5·0% per year) in western and northern Europe, a moderate decline in central Europe, and a slight decline (about –2·0% per year) in southeastern Europe (figure 3; appendix p 18).

At the European scale, the estimated country-averaged number of premature deaths per 100 000 people attributed to air pollution would potentially reduce by 9·5 deaths per 10^5 people (95% CI 6·3–11·4) by increasing the mean city tree coverage from the current (2019) tree cover to 30% (appendix p 19). The estimated number of prevented deaths varied widely among regions (figure 4), with lower rates (<10 prevented deaths per 10^5 people) in western and northern Europe, and higher rates (>20 prevented deaths per 10^5 people) in eastern Europe and in eastern and southeastern Europe (ie, North Macedonia, Serbia, Montenegro, and Kosovo). By increasing the mean tree coverage to 30% in each city, the annual mortality rate would potentially decrease on average by 8·0 deaths per 10^5 people in EU-28.

By reducing the mean city tree coverage from the current tree cover to a hypothetical no tree scenario would potentially increase the number of premature deaths by 8·2 deaths per 10^5 people (95% CI 5·4–9·7; appendix p 19). The estimated excess mortality varied among regions (figure 5), with high increases in Bosnia and Herzegovina, Poland, and Slovakia (>25 deaths per 10^5 people), and lower increases in Malta, Iberian Peninsula, and Fennoscandia (<5 deaths per 10^5 people). In EU-28, the estimated annual mortality rate would increase on average by 7·9 deaths per 10^5 people by removing all urban trees.

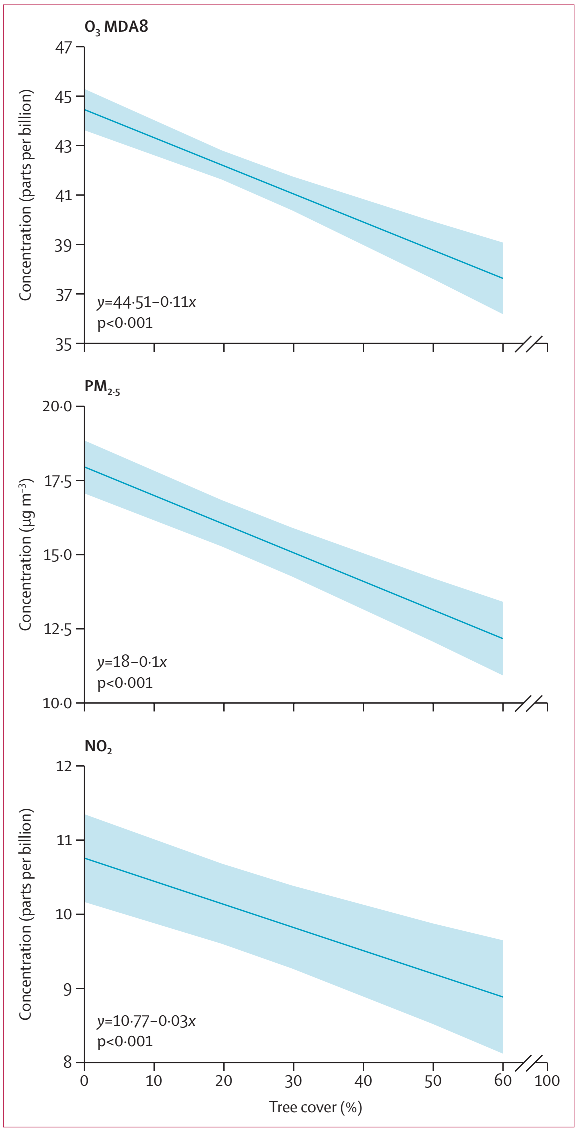

Figure 2: **Linear mixed models of $PM_{2·5}$, NO_2, and O_3 MDA8 mean concentrations**
Changes in the annual $PM_{2·5}$ and NO_2 mean concentrations and the summertime average of the daily 8-h maximum ozone concentration (O_3 MDA8) due to the increase in the yearly tree cover as estimated by the linear mixed model. The shaded areas represent the 95% CIs.

Across the 36 European countries, the estimated annual $PM_{2·5}$-attributable mortality burden could potentially be reduced by 9·4% with increasing tree coverage from the current tree cover to 30% for each city—ie, 9070 (95% CI 6946–10 096) potentially prevented deaths (appendix pp 20–21). Similarly, the estimated annual NO_2-attributable mortality burden could be reduced by 7·2%—ie, 2526 (95% CI 646–3735) potentially prevented deaths (appendix pp 22–23). With a mean tree coverage of 30%, the annual number of O_3-attributable deaths could potentially be reduced by 12·1%—ie, 378 (95% CI 183–559) prevented

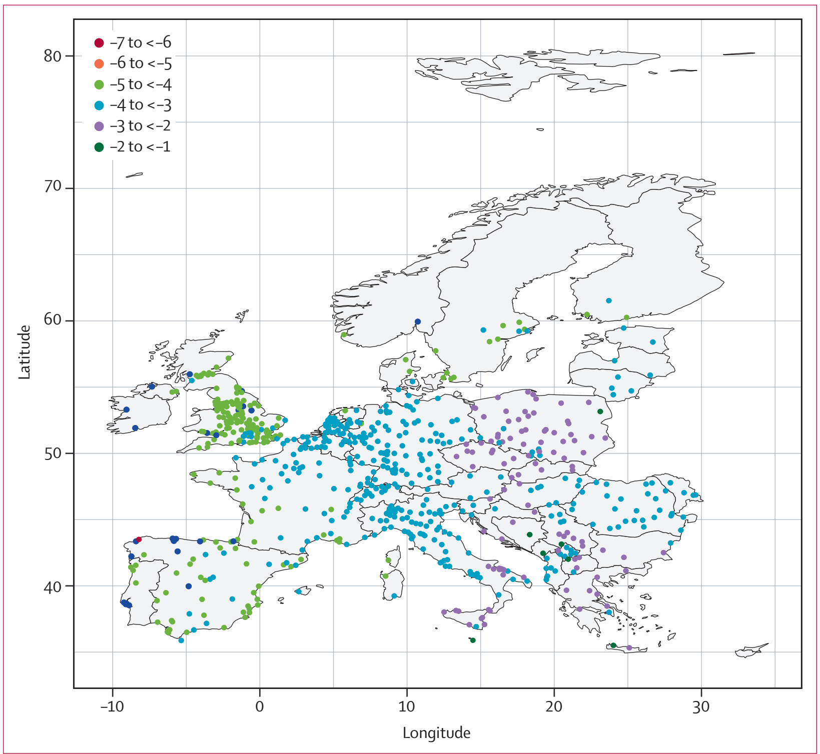

Figure 3: **Slope of the trends of the yearly number of city-level premature deaths, per 100 000 people (in percentage per year) from 2000 to 2019**

deaths (appendix pp 24–25). By reducing the mean city tree coverage from the current tree cover to a hypothetical no tree scenario could increase the estimated number of $PM_{2·5}$-attributable deaths by 19·5%—ie, a potential excess of 18 847 premature deaths (95% CI 14 492–20 941; appendix pp 20–21). The annual NO_2-attributable mortality burden could potentially increase by 15·0%—ie, 5242 (95% CI 1346–7726) excess deaths (appendix pp 22–23). The annual O_3-attributable premature deaths could increase by 22·7% with no tree cover—ie, 706 (95% CI 341–1045) potentially excess deaths (appendix pp 24–25).

Across the 744 European urban centres with over 50 000 inhabitants, 11 974 (95% CI 7775–14 390) premature deaths could potentially be prevented by expanding tree coverage to 30% for each urban centre compared with the current coverage scenario—ie, roughly 8·9% of the deaths due to air pollution effects could potentially be prevented (figure 6; appendix p 26). In 2019, we estimated that the urban trees have potentially prevented a total of 24 795 (95% CI 16 179–29 712) premature deaths attributed to air pollution (in comparison with the same urban centres without trees)—ie, 18·4% of the air pollution-related premature deaths. In EU-28, increasing the mean tree coverage to 30% for each urban centre could potentially prevent 10 771 premature deaths, whereas the urban trees have potentially prevented about 23 600 premature deaths caused by air pollution in 2019.

By uniformly increasing tree cover by 5% in the 744 urban centres yielded to 2·4 (95% CI 1·1–3·8) fewer annual premature deaths per 100 000 people (appendix p 27). Compared with 2019, a five percentage point increase in tree canopy for each urban centre, for example, in areas containing non-tree vegetation, could lead to a potential reduction of 4727 (95% CI –7475 to –2067) deaths annually (ie, roughly 3·6% of air pollution-related deaths; figure 6). A 10 percentage point, 20 percentage point, and 30 percentage point increase in tree canopy cover for each urban centre would be associated with a potential reduction of 9469 deaths (4·9 deaths per 100 000 people), 19 000 deaths (9·8 deaths per 100 000 people), and 28 573 deaths (14·8 deaths per 100 000 people), annually.

Discussion

Tree canopy cover is a key element in assessing most of ecosystem services provided by the forest.[39] Nowak and Greenfield analysed tree canopy coverage at global scale using MODIS derived Urban Land Cover data at 500 m spatial resolution for urban centres dominated by the built-up environment (>50%).[40] In 2017, the average urban tree cover was 30% in Europe.[40] Moreover, the world's urban tree cover noted a slight decline (–0·2%) between 2012 and 2017, whereas a slight increase was reported in Europe (0·3%).[40] In this study, we found an average urban tree cover of 18·8% (SD 9·8) in Europe in 2017, and the urban tree cover noted a statistically significant increase between 2012 and 2017 (0·29%). We found that the averaged urban tree cover change in Europe (2012–2017) was similar by using either our approach or MODIS derived Urban Land Cover data, whereas the urban tree canopy coverage was much lower in urban centres (18·8% *vs* 30·0%). In our approach, the urban centre boundaries are not limited to built-up environment (>50%) only but defined by density (≥1500 people) and total population (≥50 000)—ie, the less populated areas and large parks are excluded. The densely populated areas have less tree coverage, for instance a 22% lower mean city tree coverage in the USA with more impervious surface cover, such as asphalt.[41]

In 744 European cities, the mean urban tree coverage was 18·5% from 2000 to 2019, and 18·7% in 2015. The lowest tree coverages (<7%) were mainly observed in former Yugoslavia (ie, Bosnia and Herzegovina, North Macedonia, Serbia, Montenegro, and Kosovo), affected by the war between 1991 and 2001 during which urban trees were massively cut for domestic heating and cooking.[42] In 93 European cities, a mean city tree coverage, obtained from the Copernicus Land Monitoring Service at a 250 m spatial resolution, of 14·9% was reported for 2015 (ie, 14·9% in Oslo, 25·4% in Edinburgh, 8·4% in Barcelona, and 13·0% in Naples).[6] In our study, we found a mean urban tree cover of 24·1% in Oslo, 15·0% in Edinburgh, 16·2% in Barcelona, and 32·0% in Naples. The differences between both studies can be explained by different urban centre delineation (eg, different to administrative boundaries) and the higher spatial resolution of the Landsat data (about 30 m) that enhances the mapping of tree cover. In previous studies, using MODIS VCF, Landsat, or Copernicus Land Monitoring Service, only trees that are 5 m or taller were mapped,[21] whereas in our approach, we adjusted the minimum height of woody vegetation from 5 m to 3 m at the Landsat pixel scale.[18]

A few studies assessed changes in tree cover across cities worldwide; for example, in 577 cities in China with an area larger than 100 km² from 2000 to 2020 by using satellite observations (MODIS product MOD44B v6) at a 250 m spatial resolution.[43] The nationwide mean urban tree cover increased by 0·07% (SD 0·51) per year.[43] Inversely, in 20 cities in the USA, tree cover was reduced by on average 0·27% per year between 2003 and 2009 and by 0·20% annually over the 5-year period of 2009–14.[44] In Europe, using about 30 m Landsat data archive in both urban and rural areas, Turubanova and colleagues[22] showed that the tree canopy cover extended by 0·9% between 2001 and 2021, with the largest increase observed in the British Isles (10·7%) and Balkan peninsula (7·1%), and slighter increases in eastern Europe (5·8%) and Iberian Peninsula (4·0%). The tree canopy cover declined in Fennoscandia (–3·5%), Baltic States (–2·5%) and western Europe (–0·3%). In this study, with a ≥3 m tree height threshold, the mean urban tree coverage increased by about 4·0% over the past two decades across Europe. The largest increase occurred in the British Isles (9·4%) and eastern Europe (8·1%), moderate increases in Balkan Peninsula (4·6%) and Baltic States (4·2%), and slight increases in Iberian Peninsula (2·8%,) and western Europe (1·2%). We also found a strong reduction in tree canopy cover in Fennoscandia (–11·3%).

Importantly, it seems that the countries with a higher mean tree cover, and less air pollution and climate change effects, have had a loss of tree cover (eg, Finland, Norway, Switzerland, and Sweden). Except in urban centres in Fennoscandia, urban tree cover loss or gain is relatively small, with varying changes at the local scale. In urban centres, trees and terrestrial ecosystems are under threat from urbanisation but also the effects of climate change (eg, increased drought and crown defoliation), air pollution, old age, pests and diseases, and intensive recreational use, tend to reduce tree cover in heavily populated areas.[44,45] Inversely, the expanding tree cover can be mainly attributed to crown growth, natural regeneration, and greening strategies to mitigate the air pollution and climate change effects.[44,46] In Europe, recent planting efforts following the *EU Biodiversity Strategy for 2030*, committing to plant at least 3 billion additional trees in the EU by 2030, are expected to produce greater gains in mean city tree coverage in the future.

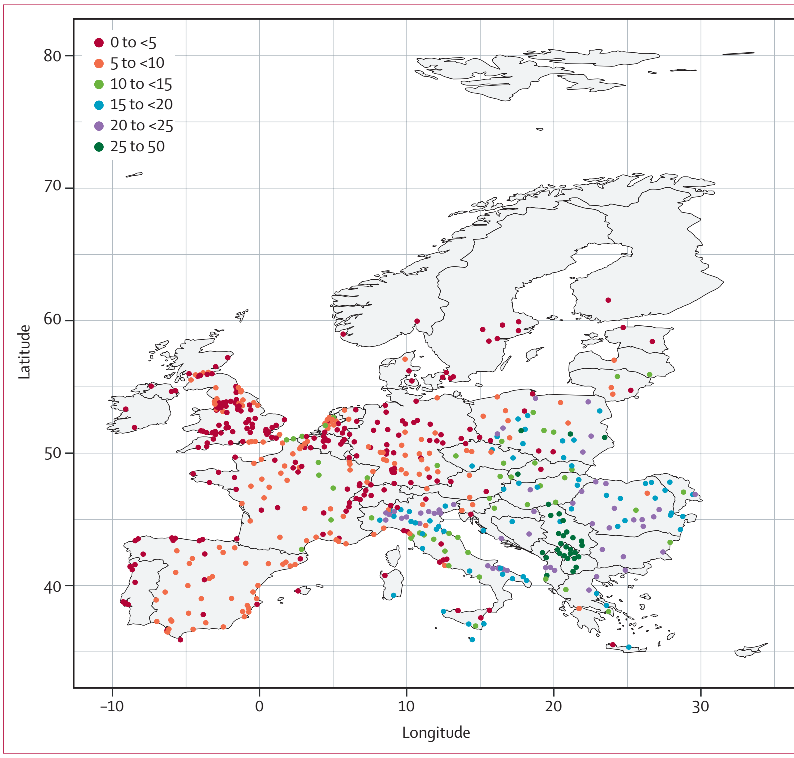

Figure 4: **Number of prevented deaths (per 100 000 people) by increasing tree coverage from the current tree cover (2019) to a mean tree coverage of 30% for each urban area**

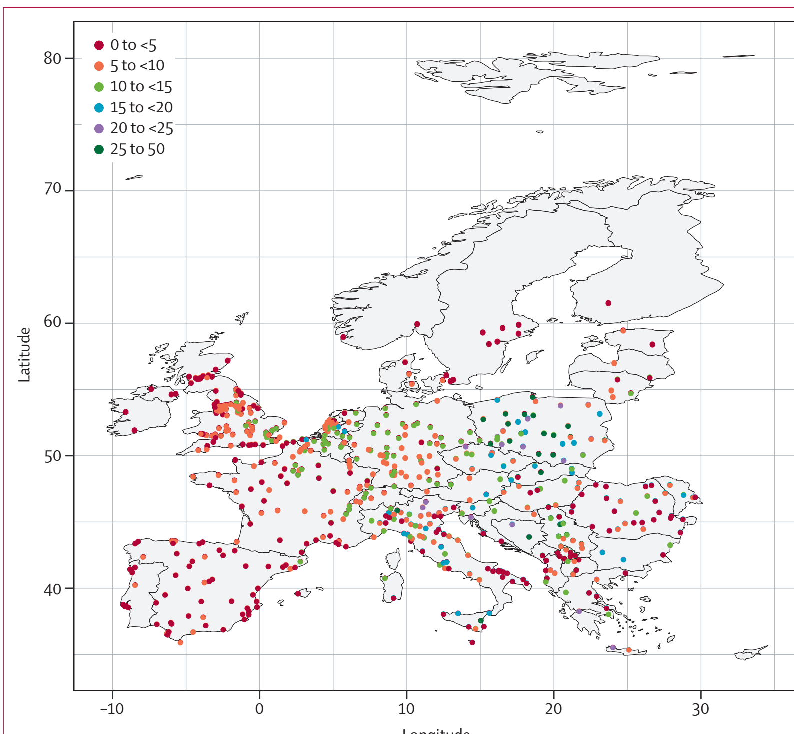

Figure 5: **Number of additional premature deaths (per 100 000 people) by reducing mean tree coverage from the current tree cover (2019) to a hypothetical no tree scenario for each urban area**

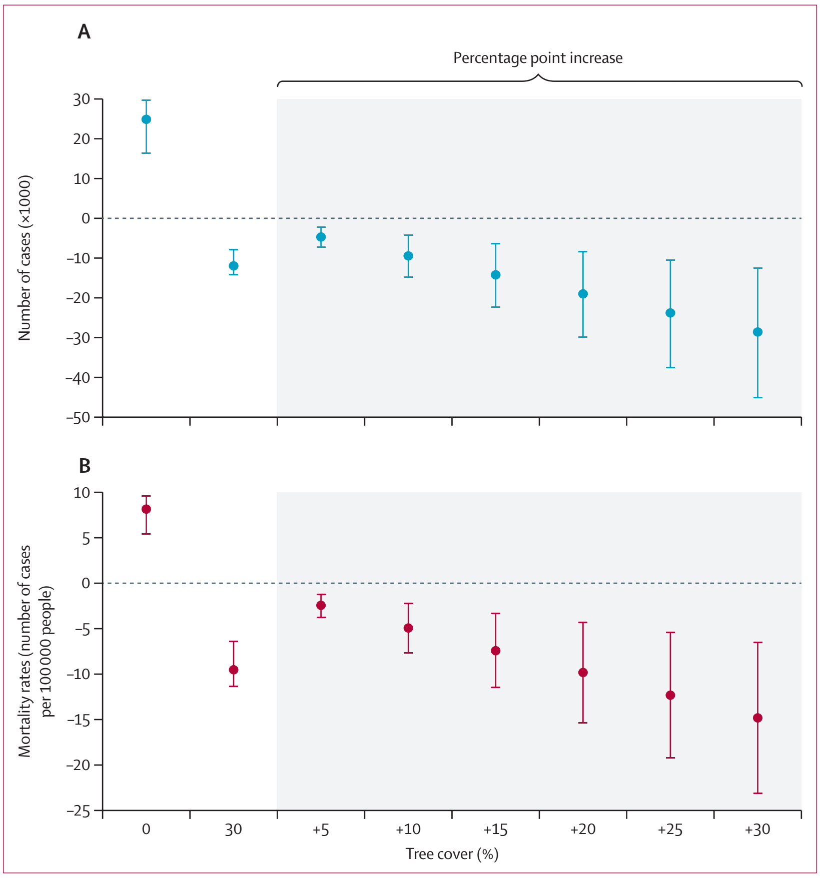

Figure 6: **Number of air pollution-related premature deaths by increasing the current tree cover for each urban area**
Difference of the total number of non-accidental premature deaths attributed to air pollution (A) and mortality rates (B) between the current tree cover (2019) and a hypothetical no tree scenario (0% tree cover), a mean city tree coverage of 30% (30% tree cover), and each five percentage point increase in tree canopy cover for each urban area compared with 2019.

Air pollution is a worldwide threat, with surface O_3, NO_2 and $PM_{2·5}$ being among the most harmful pollutants for citizens' health.[4] Over the past two decades, most urban centres meeting WHO's air quality guidelines for $PM_{2·5}$ and NO_2 were in Europe,[4,27,29] whereas largest O_3 exceedances were observed in southeastern Europe and O_3 declined in northern Europe (eg, Finland and Norway) and southeastern Europe (eg, Albania, North Macedonia, Romania, and Kosovo; appendix pp 28–29).[4,47] Although urban greening might improve air quality at city scale, it could have detrimental effects at street level depending on vegetation type and urban form.[48,49] However, abundant literature showed that urban trees can reduce air pollution at the city-wide scale.[7,46,50]

In this study, the model estimates that increasing tree cover at urban centre level would significantly reduce the summertime O_3 MDA8 concentrations and annual NO_2 and $PM_{2·5}$ mean concentrations. We estimated that each five percentage point increase in tree canopy cover would reduce the annual NO_2 and $PM_{2·5}$ mean concentrations and summertime O_3 MDA8 concentrations by 1·4%, 2·8%, and 1·2%, respectively. Our findings revealing improvement of air quality by urban tree-cover support our hypothesis and previous studies (appendix pp 30–31). The estimated air quality improvements due to urban trees are relatively low at the city scale, although more relevant in highly tree-covered areas. In this study, the model estimates that a hypothetical 100% tree cover (ie, contiguous forest stands) would reduce the summertime O_3 MDA8 concentrations and annual $PM_{2·5}$ and NO_2 mean concentrations by 24·7%, 55·6%, and 27·8%, respectively (appendix pp 30–31).

To date, many studies support that urban trees provide substantial health benefits.[51] In previous studies, higher canopy cover was associated with an array of public health effects, and lower all-causes mortality.[8,10,20] Exposure to ≥30% compared with 0–9% tree canopy was associated with reduced risk of dementia,[15] psychological distress,[13] and prevalent cardiovascular diseases.[16] Moreover, a significant inverse relationship between surrounding greenness, within a buffer of 500 m around home, and all-cause mortality has been observed.[9]

Our results showed considerable variability between city-level and country-level mortality rates, due to environmental conditions, air pollution levels, and socioeconomic aspects (eg, Gross Domestic Product). The highest mortality burdens related to $PM_{2·5}$, NO_2, and O_3 were observed in southern and eastern Europe, particularly in southeastern Europe (ie, Bosnia and Herzegovina, North Macedonia, Serbia, Montenegro, and Kosovo), whereas those with the lowest mortality attributable to air pollution effects were mainly located in northern Europe (including Finland, Ireland, and Norway), similarly to urban heat island effects on mortality.[6]

Across the 744 European urban centres with over 50 000 inhabitants, we estimated that 11 974 premature deaths (9070 $PM_{2·5}$-attributable, 2526 NO_2-attributable, and 378 O_3-attributable deaths) could potentially be prevented annually by increasing tree coverage to 30% for each urban centre compared with the current coverage scenario (ie, roughly 8·9% of the total air pollution-related mortality). Compared with 2019, each five percentage point increase in tree canopy cover for each urban centre could lead to a potential 3·6% reduction of air pollution-related mortality annually (about 4800 deaths). By comparison, Khomenko and colleagues[54] estimated that compliance with WHO air quality guidelines could have prevent 51 213 $PM_{2·5}$-related and 900 NO_2-related deaths for 2015 for adults in 1016 cities in Europe. Pereira Barboza and colleagues[20] estimated that 17 947 (95% CI 0–35 747) natural-cause deaths (of people aged ≥20 years) could be prevented annually (which represents 0·9% of the total natural-cause mortality) in 1027 cities across 31 European countries if cities complied with WHO recommendations by increasing the percentage of green area to 25%. In 93 European cities, Iungman and colleagues[6] estimated that 2644 premature deaths (for those aged ≥20 years) could be prevented by expanding city tree coverage to 30% due to a mean city cooling of 0·4°C. In Philadelphia, USA, a five percentage point and ten percentage point increase in tree canopy could result in a reduction of 302 deaths and 376 deaths, respectively, citywide annually for adult residents between 2014 and 2025.[10]

At the European scale, most studies analysed tree canopy cover within cities using digital cover mapping procedures or photo-interpretation at spatial resolution exceeding 250 m.[6,20,40,43] To estimate tree cover changes over time, the MODIS VCF product is widely used worldwide, but an underestimation at the lower-to-middle range of tree cover (20–60%) and an overestimation at lower tree cover (<20%) exist.[55] Among other strengths, our study includes the use of satellite imagery at high-resolution grid-cell level of about 30 m covering 744 European cities to investigate the change in yearly tree canopy cover. We acknowledge that the dataset by Potapov and colleagues[23,36] might underestimate urban tree canopy cover, particularly in densely populated urban areas, due to its global training focus, which prioritises mapping forest cover over finer urban tree details; however, it provides consistent, high-resolution data across all study areas and timeframes, which is essential for large-scale analysis.[23,36] To accurately estimate the tree canopy coverage at city-scale, assessment from very-high resolution remote sensing images using deep learning, such as at 0·3–0·5 m fine-scale, has been used for cities such as in Brazil or France.[11,56] In addition, MODIS VCF or Landsat only maps trees that are 5 m or taller,[21] whereas in our approach we adjusted the minimum tree height from 5 m to 3 m at the Landsat pixel scale.[18] This modification better accommodates the significant variation in tree species height across Europe,[57] particularly in urban settings where landscaping choices lead to an increase in species richness,[58] thus also including shorter tree varieties.[59] The revised threshold ensures that our analysis inclusively captures smaller yet ecologically significant tree cover, providing a more accurate and ecologically relevant assessment of urban tree coverage. From satellite imagery with a spatial resolution of 30 m, we did not consider the variability in tree species and their different effects on air pollution, such as through emissions of biogenic volatile organic compounds that are O_3-precursors (eg, blue gum or pubescent oak).[7,60] Introducing additional information on tree composition in the model, such as using an object-based classification from very-high resolution satellite imagery,[11] might improve the accuracy of the estimations.

For the first time, this study estimated the effect of mean tree cover on $PM_{2·5}$-related, NO_2-related, and O_3-related mortality for people (all ages) living in 744 European cities from 2000 to 2019 at a high-resolution grid-cell level. We also estimated the number of deaths that could potentially be avoided by increasing tree coverage to 30% for each urban centre, for each five percentage point increase in tree canopy compared with 2019, and how much the present trees prevent premature deaths due to air pollution effects in each urban centre in 2019. Previous studies on greenery and human health used single-day estimates, such as maximum tree cover values during summer, and focused on adults and preventable mortality burden for 1 year in some European cities by using green space proxies at coarser grid-cell resolution (>250 m).[6,20,61]

In this study, the annual $PM_{2·5}$-attributable, O_3-attributable, and NO_2-attributable mortality burden were estimated using annual country-specific and cause-specific baseline incidence rates from 2000 to 2019, whereas we did not account for age structure and city-specific relative risks values. Indeed, we used relative risks for European regions based on WHO recommendations for comparability of results across countries, assuming equivalent risk of mortality for diverse settings and populations. The relative risk values varied widely among countries (appendix p 6).[62] The use of city-level mortality rates and relative risk values would add an additional level of precision, as well as a more detailed stratification by age, sex, and pre-existing health conditions could provide insights into the specific vulnerabilities within urban populations. Although mortality is an extreme endpoint, we did not investigate potential effects on hospital admissions and wellbeing (eg, mental health). The individual exposure estimates are also biased because only the outdoor exposure to air pollutants was considered, whereas people spend 80–90% of their time indoors, leading to a risk over-estimation.[63] The mobility of citizens and spatial variability of air pollutants levels were also ignored, thus assuming that all citizens are exposed to the same levels of air pollutants. In this study, the potential non–linear, synergic, and additive or inhibitor effects of combined air pollutants exposures and confounders (eg, extreme heat) on mortality were not investigated. The linear model does assume that the spatial relationship between pollution levels and health outcomes is constant across regions. Given the diversity in urban settings across Europe, this assumption might not always hold. Our all-ages and multi-pollutants approach provides a comprehensive assessment capturing the potential public health benefits from urban greening. However, due to assumptions and study limitations, the findings could be overestimated, although we emphasise these estimates should be interpreted as indicative.

Reaching a mean tree coverage of 30% could be challenging or unattainable, particularly in dense built-up areas and densely populated cities or in cities facing water scarcity.[12,45] To meet the recommended 30% tree canopy cover, tree planting programmes need to target not only public spaces but especially private spaces such as residential yards, as well as peri-urban areas (appendix p 32).[11,53,65] In conclusion, our results highlighted the potential health benefits of increasing tree coverage in urban environments. Green space planning and air pollution control can jointly improve public health.[48] Although the benefits of urban trees have been neglected by policymakers until the past decade, we encourage city planners and decision-makers to incorporate urban green infrastructure adapted to local settings in combination with emissions control strategies and other interventions (eg, cold air corridor or green roofs) to maximise public health benefits and citizens' wellbeing, which would also result in more sustainable and climate-resilient cities in the long-term.

Contributors

PS contributed to the study conception and design, data collection and analysis, and wrote, commented on, and revised the manuscript. I-SP contributed to the data collection and analysis. SL and SP contributed to data collection. ADM and EP revised the manuscript. EA contributed to the study conception, and commented on and revised the manuscript. VC contributed to the conception of study, data collection and analysis, and commented on and revised the first draft of the manuscript. All authors participated in revising the manuscript. All authors read and approved the final manuscript. All authors had full access to all the data in the study, and had final responsibility for the decision to submit for publication.

Declaration of interests

We declare no competing interests.

Data sharing

All data are present in the Article or appendix. Additional data related to this Article can be requested from the corresponding author.

Acknowledgments

This work was made in the framework of Research Group 8.04.00 on air pollution and climate change) of the International Union of Forest Research Organizations, a non-profit organisation. This work was carried out with the contribution of the LIFE financial instrument of the EU in the framework of the AIRFRESH project on air pollution removal by urban forests for a better human wellbeing (LIFE19 ENV/FR/000086) and by the Romanian National Research Authority within the FORCLIMSOC Nucleu Programme (contract 12N/2023, project number PN 23090101). VC thanks projects URBFLUX (PID2021–125941OB-I00) funded by MCIN/AEI/10.13039/501100011033, and The European Regional Development Fund and EVER (Programa PROMETEO 2022) funded by Generalitat Valenciana. EA acknowledges support from the National Natural Science Foundation of China (4210070867) and the Jiangsu Distinguished Professor programme of the People's Government of Jiangsu Province, China. EP thanks the National Recovery and Resilience Plan (Mission 4 Component 2 Investment 1.4: call for tender number 3138 of Dec 16, 2021, rectified by decree number 3175 of Dec 18, 2021 of Italian Ministry of University and Research funded by the EU [NextGenerationEU]); project code CN_00000033, concession decree number 1034 of June 17, 2022, adopted by the Italian Ministry of University and Research (CUP B83C22002930006 on national biodiversity future centre).

Editorial note: The Lancet Group takes a neutral position with respect to territorial claims in published maps and institutional affiliations.

References

1 Fuller R, Landrigan PJ, Balakrishnan K, et al. Pollution and health: a progress update. *Lancet Planet Health* 2022; **6:** e535–47.

2 Lovett GM, Tear TH, Evers DC, et al. Effects of air pollution on ecosystems and biological diversity in the eastern United States. *Ann N Y Acad Sci* 2009; **1162:** 99–135.

3 UN Habitat. World cities report 2022: envisaging the future of cities. United Nations Human Settlements Programme, 2022.

4 Sicard P, Agathokleous E, Anenberg SC, De Marco A, Paoletti E, Calatayud V. Trends in urban air pollution over the last two decades: a global perspective. *Sci Total Environ* 2023; **858:** 160064.

5 Ballester J, Quijal-Zamorano M, Méndez Turrubiates RF, et al. Heat-related mortality in Europe during the summer of 2022. *Nat Med* 2023; **29:** 1857–66.

6 Iungman T, Cirach M, Marando F, et al. Cooling cities through urban green infrastructure: a health impact assessment of European cities. *Lancet* 2023; **401:** 577–89.

7 Manzini J, Hoshika Y, Carrari E, et al. FlorTree: a unifying modelling framework for estimating the species-specific pollution removal by individual trees and shrubs. *Urban For Urban Green* 2023; **85:** 127967.

8 van den Berg M, Wendel-Vos W, van Poppel M, Kemper H, van Mechelen W, Maas J. Health benefits of green spaces in the living environment: a systematic review of epidemiological studies. *Urban For Urban Green* 2015; **14:** 806–16.

9 Rojas-Rueda D, Nieuwenhuijsen MJ, Gascon M, Perez-Leon D, Mudu P. Green spaces and mortality: a systematic review and meta-analysis of cohort studies. *Lancet Planet Health* 2019; **3:** e469–77.

10 Kondo MC, Mueller N, Locke DH, et al. Health impact assessment of Philadelphia's 2025 tree canopy cover goals. *Lancet Planet Health* 2020; **4:** e149–57.

11 Sicard P, Coulibaly F, Lameiro M, et al. Object-based classification of urban plant species from very high-resolution satellite imagery. *Urban For Urban Green* 2023; **81:** 127866.

12 Konijnendijk CC. Evidence-based guidelines for greener, healthier, more resilient neighbourhoods: introducing the 3-30-300 rule. *J For Res* 2023; **34:** 821–30.

13 Astell-Burt T, Feng X. Association of urban green space with mental health and general health among adults in Australia. *JAMA Netw Open* 2019; **2:** e198209.

14 Bratman GN, Anderson CB, Berman MG, et al. Nature and mental health: an ecosystem service perspective. *Sci Adv* 2019; **5:** eaax0903.

15 Astell-Burt T, Navakatikyan MA, Feng X. Urban green space, tree canopy and 11-year risk of dementia in a cohort of 109 688 Australians. *Environ Int* 2020a; **145:** 106102.

16 Astell-Burt T, Feng X. Urban green space, tree canopy and prevention of cardiometabolic diseases: a multilevel longitudinal study of 46 786 Australians. *Int J Epidemiol* 2020b; **49:** 926–33.

17 Owen D, Fitch A, Fletcher D, et al. Opportunities and constraints of implementing the 3-30-300 rule for urban greening. *Urban For Urban Green* 2024; **98:** 128393.

18 Browning MHEM, Locke DH, Konijnendijk C, et al. Measuring the 3-30-300 rule to help cities meet nature access thresholds. *Sci Total Environ* 2024; **907:** 167739.

19 Ziter CD, Pedersen EJ, Kucharik CJ, Turner MG. Scale-dependent interactions between tree canopy cover and impervious surfaces reduce daytime urban heat during summer. *Proc Natl Acad Sci USA* 2019; **116:** 7575–80.

20 Barboza EP, Cirach M, Khomenko S, et al. Green space and mortality in European cities: a health impact assessment study. *Lancet Planet Health* 2021; **5:** e718–30.

21 DiMiceli CM, Carroll ML, Sohlberg RA, et al. Annual global automated MODIS vegetation continuous fields (MOD44B) at 250 m spatial resolution for data years beginning day 65, 2000–2014, collection 5 percent tree cover, version 6. University of Maryland, 2017.

22 Turubanova S, Potapov P, Hansen MC, et al. Tree canopy extent and height change in Europe, 2001–2021, quantified using Landsat data archive. *Remote Sens Environ* 2023; **298:** 113797.

23 Potapov P, Hansen MC, Pickens A, et al. The global 2000–2020 land cover and land use change dataset derived from the Landsat archive: first results. *Front Remote Sens* 2022; **3:** 856903.

24 Florczyk A, Corbane C, Schiavina M, et al. GHS Urban Centre Database 2015, multitemporal and multidimensional attributes. European Commission, 2019.

25 Liu F, Wang S, Xu Y, Ying Q, Yang F, Qin Y. Accuracy assessment of Global Human Settlement Layer (GHSL) built-up products over China. *PLoS One* 2020; **15:** e0233164.

26 Apte J, Seraj S, Chambliss S, et al. Air inequality: global divergence in urban fine particulate matter trends. *ChemRxiv* 2021; published online May 26. https://doi.org/10.26434/chemrxiv.14671908.v1 (preprint).

27 Anenberg SC, Mohegh A, Goldberg DL, et al. Long-term trends in urban NO_2 concentrations and associated paediatric asthma incidence: estimates from global datasets. *Lancet Planet Health* 2022; **6:** e49–58.

28 Malashock DA, Delang MN, Becker JS, et al. Estimates of ozone concentrations and attributable mortality in urban, peri-urban and rural areas worldwide in 2019. *Environ Res Lett* 2022; **17:** 054023.

29 Southerland VA, Brauer M, Mohegh A, et al. Global urban temporal trends in fine particulate matter ($PM_{2·5}$) and attributable health burdens: estimates from global datasets. *Lancet Planet Health* 2022; **6:** e139–46.

30 Vos T, Lim SS, Abbafati C, et al. Global burden of 369 diseases and injuries in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. *Lancet* 2020; **396:** 1204–22.

31 Lefohn AS, Malley CS, Smith L, et al. Tropospheric ozone assessment report: global ozone metrics for climate change, human health, and crop/ecosystem research. *Elementa* 2018; **1:** 1.

32 Boogaard H, Samoli E, Patton AP, et al. Long-term exposure to traffic-related air pollution and non-accidental mortality: a systematic review and meta-analysis. *Environ Int* 2023; **176:** 107916.

33 Chen J, Hoek G. Long-term exposure to PM and all-cause and cause-specific mortality: a systematic review and meta-analysis. *Environ Int* 2020; **143:** 105974.

34 Faustini A, Rapp R, Forastiere F. Nitrogen dioxide and mortality: review and meta-analysis of long-term studies. *Eur Respir J* 2014; **44:** 744–53.

35 WHO. Review of evidence on health aspects of air pollution: REVIHAAP project. World Health Organization, Regional Office for Europe, 2021.

36 Potapov P, Li X, Hernandez-Serna A, et al. Mapping global forest canopy height through integration of GEDI and Landsat data. *Remote Sens Environ* 2021; **253:** 112165.

37 Ock YJ, Shandas V, Ribeiro F, Young N. Drivers of tree canopy loss in a mid-sized growing city: case study in Portland, OR (USA). *Sustainability (Basel)* 2024; **16:** 1803.

38 Bates D, Maechler M, Bolker B, Walker S. Fitting linear mixed-effects models using lme4. *J Stat Softw* 2015; **67:** 1–48.

39 Chen G, Singh KK, Lopez J, Zhou Y. Tree canopy cover and carbon density are different proxy indicators for assessing the relationship between forest structure and urban socio-ecological conditions. *Ecol Indic* 2020; **113:** 106279.

40 Nowak DJ, Greenfield EJ. The increase of impervious cover and decrease of tree cover within urban areas globally (2012–2017). *Urban For Urban Green* 2020; **49:** 126638.

41 McDonald RI, Biswas T, Sachar C, et al. The tree cover and temperature disparity in US urbanized areas: quantifying the association with income across 5723 communities. *PLoS One* 2021; **16:** e0249715.

42 Lacan I, McBride JR. War and trees: The destruction and replanting of the urban and peri-urban forest of Sarajevo, Bosnia and Herzegovina. *Urban For Urban Green* 2009; **8:** 133–48.

43 Leng S., Sun R., Yang X., Jin M., Chen L. Diverse types of coupling trends in urban tree and nontree vegetation associated with urbanization levels. *npj Urban Sustain* 2023; **3:** 33.

44 Nowak DJ, Greenfield EJ. Declining urban and community tree cover in the United States. *Urban For Urban Green* 2018; **32:** 32–55.

45 Begert B. Cities want more trees. Drought is complicating their efforts. Oct 18, 2022. https://grist.org/drought/cities-want-more-trees-drought-is-complicating-their-efforts (accessed on June 3, 2024).

46 Hewitt CN, Ashworth K, MacKenzie AR. Using green infrastructure to improve urban air quality (GI4AQ). *Ambio* 2020; **49:** 62–73.

47 Sicard P, Anav A, De Marco A, Paoletti E. Projected global ground-level ozone impacts on vegetation under different emission and climate scenarios. *Atmos Chem Phys* 2017; **17:** 12177–96.

48 Venter ZS, Hassani A, Stange E, Schneider P, Castell N. Reassessing the role of urban green space in air pollution control. *Proc Natl Acad Sci USA* 2024; **121:** e2306200121.

49 Yli-Pelkonen V, Scott AA, Viippola V, Setälä H. Trees in urban parks and forests reduce O_3, but not NO_2 concentrations in Baltimore, MD, USA. *Atmos Environ* 2017; **167:** 73–80.

50 Araminienė V, Sicard P, Černiauskas V, Coulibaly F, Varnagirytė-Kabašinskienė I. Estimation of air pollution removal capacity by urban vegetation from very high-resolution satellite images in Lithuania. *Urban Clim* 2023; **51:** 101594.

51 Tang L, Shao G, Groffman PM. Urban trees: how to maximize their benefits for humans and the environment. *Nature* 2024; **626:** 261.

52 Ren Z, Zhao H, Fu Y, Xiao L, Dong Y. Effects of urban street trees on human thermal comfort and physiological indices: a case study in Changchun city, China. *J For Res* 2022; **33:** 911–22.

53 Anav A, Sorrentino B, Collalti A, et al. Meteorological, chemical and biological evaluation of the coupled chemistry-climate WRF-Chem model from regional to urban scale. An impact-oriented application for human health. *Environ Res* 2024; **257:** 119401.

54 Khomenko S, Cirach M, Pereira-Barboza E, et al. Premature mortality due to air pollution in European cities: a health impact assessment. *Lancet Planet Health* 2021; **5:** e121–34.

55 DiMiceli C, Sohlberg R, Townshend J. MODIS/terra vegetation continuous fields yearly L3 global 250m SIN grid V061. https://lpdaac.usgs.gov/products/mod44bv061/ (accessed Feb 24, 2024).

56 Guo J, Xu Q, Zeng Y, Liu Z, Zhu XX. Nationwide urban tree canopy mapping and coverage assessment in Brazil from high-resolution remote sensing images using deep learning. *ISPRS J Photogramm Remote Sens* 2023; **198:** 1–15.

57 Fréjaville T, Fady B, Kremer A, Ducousso A, Benito Garzón M. Inferring phenotypic plasticity and local adaptation to climate across tree species ranges using forest inventory data. *bioRxiv* 2019; published Jan 23. https://dx.doi.org/https://doi.org/10·1101/527390 (preprint).

58 Morgenroth J, Östberg J, van den Bosch CK, et al. Urban tree diversity—taking stock and looking ahead. *Urban For Urban Green* 2016; **15:** 1618–8667.

59 Kendal D, Dobbs C, Lohr VI. Global patterns of diversity in the urban forest: is there evidence to support the 10/20/30 rule? *Urban For Urban Green* 2014; **13:** 411–17.

60 Sicard P, Agathokleous E, De Marco A, Paoletti E. Ozone-reducing urban plants: choose carefully. *Science* 2022; **377:** 585–585.

61 Markevych I, Schoierer J, Hartig T, et al. Exploring pathways linking greenspace to health: theoretical and methodological guidance. *Environ Res* 2017; **158:** 301–17.

62 Vicedo-Cabrera AM, Sera F, Liu C, et al. Short term association between ozone and mortality: global two stage time series study in 406 locations in 20 countries. *BMJ* 2020; **368:** m108.

63 Park YM, Kwan MP. Individual exposure estimates may be erroneous when spatiotemporal variability of air pollution and human mobility are ignored. *Health Place* 2017; **43:** 85–94.

64 Yin Y, Li S, Xing X, et al. Cooling benefits of urban tree canopy: a systematic review. *Sustainability (Basel)* 2024; **16:** 4955.

65 Sicard P, Agathokleous E, Araminienė V, et al. Should we see urban trees as effective solutions to reduce increasing ozone levels in cities? *Environ Pollut* 2018; **243:** 163–76.