Health impact assessment of Philadelphia's 2025 tree canopy cover goals

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Summary

Background Cities across the world are undertaking ambitious projects to expand tree canopy by increasing the number of trees planted throughout public and private spaces. In epidemiological studies, greenspaces in urban environments have been associated with physical and mental health benefits for city dwellers. Greenworks Philadelphia is a plan to increase tree cover across Philadelphia (PA, USA) by the year 2025. We aimed to assess whether an increase in tree canopy or greenspace in Philadelphia could decrease mortality.

Methods We did a greenspace health impact assessment to estimate the annual premature mortality burden for adult residents associated with projected changes in tree canopy cover in Philadelphia between 2014 and 2025. Using up-to-date exposure–response functions, we calculated the number of preventable annual premature deaths city-wide, and for areas of lower versus higher socioeconomic status, for each of three tree canopy scenarios: low, moderate and ambitious. The ambitious scenario reflected the city's goal of 30% tree canopy cover in each of the city's neighbourhoods; and low and moderate scenarios were based on the varying levels of plantable space across neighbourhoods.

Findings We estimated that 403 (95% interval 298–618) premature deaths overall, including 244 (180–373) premature deaths in areas of lower socioeconomic status, could be prevented annually in Philadelphia if the city were able to meet its goal of increasing tree canopy cover to 30%.

Interpretation Bringing all of Philadelphia, and particularly its poorer neighbourhoods, up to the 30% goal of tree canopy cover is not without challenge. Nevertheless, policies are warranted that value urban greening efforts as health-promoting and cost-saving measures.

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Introduction

Cities worldwide are undertaking projects to preserve and increase urban greenspace[1,2] in the face of changing climates, natural disasters, invasive pests, and ongoing development pressures.[3] Researchers and practitioners view urban greening initiatives as providing ecosystem services, supporting sustainability, and promoting liveable cities.[4–6]

Urban greenspace can be regarded as a preventive public health measure.[6,7] For individuals who have access, parks, gardens, trees, and forests can contribute to improved quality of life by improving mental health, increasing opportunities for social interactions and physical activity, and reducing stress, crime, and violence.[8] Greenspace can also affect mortality, itself. Two longitudinal studies testing the association between greenspace exposure and mortality have been done in the USA.[9,10] Wilker and colleagues[9] calculated the association between residential greenspace exposure and risk of death for 1645 people who had had a stroke between 1999 and 2008. For individuals living in the greenest areas, compared with the least green areas, risk of death was reduced (hazard ratio [HR] 0·78, 95% CI 0·63–0·97), even when adjusting for proximity of high-traffic roadways. James and colleagues[10] followed up a US-based prospective cohort of nurses between 2000 and 2008. For participants living in the greenest areas compared with the least green areas (using a short-term measure at time of death), risk of all-cause non-injury mortality was decreased (HR 0·88, 95% CI 0·82–0·94), even when adjusting for air pollution exposure.

Although previous meta-analyses exist,[11,12] Rojas-Rueda and colleagues[13] have done the first meta-analysis of greenspace exposure–mortality dose–response, using solely longitudinal studies. They considered nine studies including 8 324 652 adults from seven countries (including two from the USA).[9,10] The authors found significantly lower risk of all-cause mortality with increased residential greenspace exposure within 500 m (per 0·1 unit increase in the Normalized Difference Vegetation Index [NDVI]; HR 0·96, 95% CI 0·94–0·97).

Evidence suggests that trees in particular, compared with other forms of urban vegetation, affect human health and wellbeing.[14,15] A study of the association between self-reported health and near-residence trees, grass, and total vegetation found significantly higher reporting of very

Research in context

Evidence before this study
Ongoing urbanisation processes and competing land use interests have resulted in the disappearance of natural outdoor environments in cities. However, various epidemiological studies have associated the presence of greenspaces in urban environments with a wide range of physical and mental health benefits for city dwellers. Despite the emerging evidence base for greenspaces being an unconventional strategy for public health promotion, to our knowledge, no health impact assessment studies exist yet that provide policy makers and decision makers with a comprehensive insight into the expected magnitude of health benefits of real-life greenspace intervention proposals. Programmes that serve to increase tree canopy could potentially decrease morbidity and mortality for urban populations. In 2009, the city of Philadelphia (PA, USA) established a plan called Greenworks Philadelphia, with a policy goal for increased tree cover across the city by the year 2025.

Added value of this study
We did a greenspace health impact assessment of three scenarios for the year 2025 (low, moderate, and ambitious), with the most ambitious being the city of Philadelphia's goal of 30% tree canopy cover in each of the city's neighbourhoods, and low and moderate scenarios requiring removal of impervious surfaces. We estimated the preventable annual premature mortality burden associated with change in tree canopy cover levels, coinciding with the three scenarios. Our dose–response function is based on a meta-analysis that considered data from nine longitudinal studies including 8 324 652 adults from seven different countries (including two in the USA).

Implications of all the available evidence
A five percentage point increase in tree canopy only in areas containing non-tree vegetation could result in an annual reduction of 302 deaths city-wide, with a value of US$2·9 billion. A ten percentage point increase in canopy city-wide was associated with an estimated reduction of more than 376 deaths city-wide, and a value of $3·6 billion. 403 premature adult deaths (3% of total mortality) could potentially be prevented annually if Philadelphia accomplished its goal of increasing tree canopy cover to 30% by 2025. Areas with lower socioeconomic status would benefit the most from an increase in tree canopy cover. The predicted value translates to nearly $4 billion (2015 $US) based on the projected value of a statistical life. Urban greening programmes can be a means, aside from traditional measures, to promote public health, decrease health inequalities, and promote environmental justice.

good health for participants with high tree cover, and no association with grass cover.[15] Tree canopy is typically more effective at reducing land and air temperatures than is grass or other vegetative cover, which could be a possible mechanism.[16,17] Efforts to increase urban tree canopy cover,[18] or the proportion of land covered by tree crowns when viewed from above,[19] are a predominant form of urban greening policy. Such programmes could potentially decrease morbidity and mortality for urban populations. In a 2009 plan called Greenworks Philadelphia, the city of Philadelphia (PA, USA) established a year 2025 policy goal for increased city-wide tree cover. Although American Forests, a national conservation non-profit organisation, previously recommended a 40% tree canopy cover goal for all US cities,[20] Philadelphia set a goal of 30% cover per neighbourhood.

For the **Greenworks Philadelphia plan** see https://www.phila.gov/programs/greenworks

We constructed three build-out scenarios for year 2025, with the most ambitious being Philadelphia's goal of 30% tree canopy cover in each of the city's neighbourhoods, which would require removal of impervious surfaces across neighbourhoods, and two more tempered scenarios. We then applied a greenspace health impact assessment tool to estimate the preventable annual premature mortality burden associated with change in tree canopy cover levels, coinciding with the three build-out scenarios.

Methods

Study setting
In 2015, Philadelphia was the fifth largest city by population and sixth largest city by area in the USA (population 1·6 million; 347·6 km²).[21] However, Philadelphia was also the poorest of the ten largest cities in the USA and had higher rates of mortality compared with the US population. The applied all-cause mortality rate for the city's adult residents in 2015 was 887 deaths per 100 000 people,[22] compared with 733 deaths per 100 000 people in the USA overall.

Figure 1 shows the spatial distribution of tree canopy cover in Philadelphia, and two areas with low and high percent non-tree vegetative cover. The most recent published high resolution (1 m²) landcover data for Philadelphia at the time of this study were obtained using Light Detection and Radar (LiDAR) data and aerial imagery from 2014.[23] LiDAR data are derived from a remote sensing procedure that uses light to measure variable distances (eg, from an aeroplane) to Earth. Based on this data, tree canopy covered 20% of land area,[23] which is comparable with two nearby cities: Baltimore (MD, USA) had 28% tree canopy in 2015[24] whereas New York (NY, USA) had 21% in 2010.[25] In Philadelphia, 23% of the 2014 canopy cover was on residential land and 35% was in parks and recreational spaces.[2,26] The remaining tree canopy was on commercial, industrial, institutional, vacant, parking, utility, and other land uses. We assessed percent tree canopy cover according to census tracts, which are a surrogate for neighbourhood. Of 384 census tracts in Philadelphia, 80 already meet or exceed the 30% tree canopy cover goal, and 103 census tracts could meet the goal by planting trees in areas currently covered with grass or shrubs.[27] The remaining

200 tracts would require removal of impervious surfaces (such as paving or buildings) to meet the goal, which involves more effort and resources.

In Philadelphia, socioeconomic status and tree canopy are closely tied. Median household income strongly coincides with overall greenness levels in neighbourhoods,[28] and neighbourhoods of lower socioeconomic status tend to have fewer trees or less vegetation than do areas of higher socioeconomic status.

Study approach and data

We did a quantitative health impact assessment of all-cause mortality burden for adult residents (aged ≥18 years) in Philadelphia based on three tree canopy build-out scenarios for the year 2025, modelling changes at the level of US census tracts. For all three scenarios, we assigned census tracts that had 30% or more tree canopy cover in 2014 (ie, those already meeting the municipal goal) a value of 0% increase. For other census tracts, scenarios were constructed for low, moderate, and ambitious increases in tree canopy cover. For the low increase scenario, up to an additional five percentage point increase in tree canopy cover (not exceeding 30% total tree canopy cover) only in census tracts that have any permeable plantable space (ie, non-tree vegetative landcover).[27] This scenario accounts for the fact that it is difficult to plant trees in existing impervious surfaces (ie, by removal of paving or buildings). For the moderate increase scenario, a ten percentage point increase in tree canopy cover (not exceeding 30% total tree canopy cover) by census tract city-wide on any surface, irrespective of surface permeability. For the ambitious increase target, an increase of up to 30% tree canopy cover within census tracts city-wide, irrespective of permeability of the surface. This target is the stated policy goal for 2025 in the Greenworks Philadelphia plan.

We calculated projected changes in all-cause mortality associated with increases in tree canopy cover at the census tract level, using population data and the most up-to-date mortality rates for adult residents (aged ≥18 years) from 2015. We averaged the estimated changes in mortality by quantile of tree canopy cover at the census tract level (year 2014).

We used the mortality–greenspace dose–response function described by Rojas-Rueda and colleagues.[13] Although Philadelphia's goals specify percent tree cover, estimates for the relation between greenspace and mortality are widely based on relations with the NDVI. Nearly all studies included in the meta-analyses by Rojas-Rueda and colleagues[13] used the NDVI. Therefore, we needed to translate percentage tree cover into NDVI for Philadelphia.

NDVI provides a measure of vegetation density based on the difference between visible red and near-infrared surface reflectance in Land Remote-Sensing Satellite System (Landsat) images. We derived NDVI values from images taken by the US Geological Survey satellite

Figure 1: **Tree canopy cover in 2014, by census tract**
Tree canopy cover based on a landcover assessment.[23] Boundaries shown are from 2010 (census tracts, n=384). Close-up views show areas with low and high levels of grass and shrub cover.

For **Landsat 8 images** see https://earthexplorer.usgs.gov

Landsat 8, which has a 30 m×30 m spatial resolution. Landsat 8 takes a new image for a given location every 16 days.[29] We selected Aug 28, 2014, as the date when we would derive NDVI values from images, because it was a late summer cloud-free day when vegetation was at its peak greenness. NDVI values range from –1 to +1, with higher values indicating a greater density of healthy vegetation.[30] We excluded negative values from our analysis because they correspond to water and non-vegetative landcover. Administrative boundaries are redefined at each decennial census; therefore, we used the image taken of Philadelphia by Landsat 8 on Aug 28, 2014, to calculate the mean NDVI value in each census tract, according to 2010 boundaries.

We judged NDVI a good indicator of current and year 2025 tree canopy levels in Philadelphia. All calculations were done using mean NDVI values. To translate percent tree canopy to NDVI values, we compared data from 2014 landcover data with 2014 mean NDVI values.[23]

Using ordinary least-squares quadratic regression, we derived a linear relation at the census tract level between 2014 tree canopy (percent of pixels within each census tract that were tree canopy [UTC]) and 2014 mean NDVI values, in that mean $NDVI = -0{\cdot}03 + (0{\cdot}51 \times UTC^{1/2})$, and R^2 was 0·85. Using this relation, we estimated change in mean NDVI values between 2014 and 2025 for the three different scenarios of tree canopy cover. For example, a 5% increase in tree canopy (from 10% to

	All census tracts (n=375; population 1 557 306)	Census tracts of lower socioeconomic status (n=190; population 808 704)	Census tracts of higher socioeconomic status (n=185; population 748 602)
Area (hectares)	81·4 (80·7)	63·8 (50·7)	99·4 (99·8)
Population (n)	4153 (1714)	4256 (1830)	4047 (1584)
Adult deaths in 2015 (per 1000 residents)	19·9 (20·6)	30·1 (28·9)	9·3 (5·6)
Tree canopy cover (%)	20·3% (13·8)	16·6% (8·3)	24·1% (16·9)
NDVI value	0·18 (0·08)	0·17 (0·06)	0·20 (0·03)
No high school diploma (%)	17·3% (10·7)	23·9% (9·8)	10·4% (6·4)
Black (%)	43·7% (34·9)	65·1% (29·1)	21·7% (25·4)
Unemployed (%)	13·1% (8·1)	18·2% (7·9)	7·9% (3·9)
Income (US$)	43 413 (22 251)	27 566 (8489)	59 603 (20 212)
Vacant lots (%)	13·2% (7·7)	17·2% (7·8)	9·1% (4·8)
Poverty (%)	25·9% (15·2)	37·3% (11·8)	14·3% (7·5)

Data are mean (SD). Sociodemographic, population, and mortality data are from 2015; tree canopy cover data are from 2014. NDVI values range from –1 to 1, with higher values indicating higher density of healthy vegetation. NDVI=Normalized Difference Vegetation Index.

***Table 1:* Census tract characteristics**

15%) translates into a 0·04 increase in mean NDVI. A 10% increase in tree canopy (from 20% to 30%) translates into a 0·05 increase in mean NDVI. The change in NDVI for each census tract was included as an input for the health impact assessment.

We obtained mortality rates at the census tract level from the most recent vital statistics report by the Philadelphia Department of Public Health, which was for the year 2015.[22] All-cause mortality for adult residents (aged ≥18 years) are reported. Death records are tied to residential location.

We obtained data for area-level socioeconomic status from American Community Survey 5-year estimates (2011–15).[21] We created a socioeconomic index variable using a principal components analysis of six components at the census tract level: percent of the population aged 25 years or older without a high school diploma; percent of the black population; percent of the civilian population aged 16 years or older who were unemployed; percent of families with income below the poverty level ($24 250 in 2015 for a four-person household); median household income; and percent of vacant housing units. After calculating principal components, we estimated scores from the first component (Eigenvalue=3·6; 61% of total variance) for all tracts. Factor loadings were all positive (education, 0·39; unemployment, 0·35; vacant, 0·33; poverty, 0·46; black, 0·35), except for income (–0·47). Component scores had a mean value of 0. We assigned census tracts with socioeconomic index values greater than 0 as higher socioeconomic status and tracts with an index value of 0 or lower socioeconomic status. Socioeconomic data were not available for eight census tracts because of low population counts, and we excluded these tracts from the analysis.

Analyses and estimates

We scaled the risk estimates derived from Rojas-Rueda and colleagues[13] to the calculated differences in exposure levels (expressed as NDVI) in tree cover between baseline (2014) and the three tree build-out scenarios for 2025 at the census tract level, following standard quantitative health impact assessment methodologies.[31] We calculated the population attributable fraction to estimate the preventable annual premature mortality burden using the exposure level difference for each census tract. Premature (or early) deaths are attributable to behavioural or environmental risk factors that, in theory, could have been avoided if these risk factors would not have existed. We applied 95% CIs for the HR estimated by Rojas-Rueda and colleagues[13] to generate a 95% interval. We did all analyses using Stata version 15 (College Station, TX, USA).

In addition to the number of preventable annual premature deaths, we estimated the values associated with prevented loss of life expectancy or years of life lost between premature and expected mortality. We assigned each preventable premature death with the value of a statistical life (VSL) for 2015. The VSL is an estimated monetary value that society places on preventing premature mortality. It represents the value of life based, for example, on what people pay to reduce risk (eg, safety equipment), or the pay an individual would accept to increase their risk (eg, for more dangerous jobs).[32] The US Department of Transportation (DOT) frequently uses VSL to monetise (and thereby compare) policies.[33] DOT provided the estimated value of a statistical life, closest to our study period, of $9·4 million (2015 $US).[34,35]

Role of the funding source

The funders had no role in study design, data collection, data analysis, data interpretation, or writing of the report. MK, NM, and MN had access to all data in the study and all authors were responsible for the final decision to submit for publication.

Results

Nine of 384 census tracts in Philadelphia were excluded from the greenspace health impact assessment because socioeconomic data were missing (low population counts); thus, 375 tracts were included. 190 census tracts were of lower socioeconomic status and 185 were of higher socioeconomic status. Table 1 shows average area, population, adult deaths, percent tree canopy cover, and sociodemographic indicators of census tracts. The mean area of census tracts was 81·4 (SD 80·7) hectares, with census tracts of lower socioeconomic status smaller in area than those of higher socioeconomic status (63·8 [50·7] hectares *vs* 99·4 [99·8] hectares). Percent tree canopy cover (based on high-resolution landcover data) by census tract was mean 20·3% (SD 13·8), ranging from 2% to 88% (figure 2). The average percent tree canopy in census tracts of lower socioeconomic status was significantly smaller than in census tracts of higher socioeconomic status (16·6% *vs* 24%; p=0·002). The mean NDVI value was 0·18 (SD 0·08) city-wide, 0·17 (0·06) in census tracts of lower socioeconomic status and 0·20 (0·03) in census tracts of higher socioeconomic status. The mean population in 2015 per census tract was 4153 residents (SD 1714), and 19·9 adult deaths per 1000 residents were reported per census tract. The mortality rate was higher in census tracts of lower socioeconomic status compared with tracts of higher socioeconomic status (30·1 [SD 28·9] deaths per 1000 residents *vs* 9·3 [5·6] deaths per 1000 residents).

13 703 adult residents of Philadelphia died in 2015. Under the low increase scenario, with a target of a five percentage point increase in tree canopy cover only in areas with adequate non-tree vegetative cover, the average percent tree canopy increase would be 3·7% city-wide, 4·5% in census tracts of lower socioeconomic status, and 2·9% in census tracts of higher socioeconomic status (table 2). City-wide, 302 (95% interval 223–461) premature deaths were estimated to be preventable annually under the low increase scenario (table 3). More premature deaths would be prevented in census tracts of lower socioeconomic status compared with census tracts of higher socioeconomic status (190, 95% interval 140–289 *vs* 112, 83–171; p<0·0001). Under the low increase scenario, census tracts with 12–15% tree canopy cover would benefit the most, with 96 (95% interval 71–147) premature deaths annually (table 3).

Under the moderate increase scenario, with a target of a ten percentage point increase in tree canopy cover on any surface, the tree canopy percent increase would be 7·4% city-wide, 8·8% in census tracts of lower socioeconomic status, and 6·0% in census tracts of higher socioeconomic status (table 2). City-wide, 376 (95% interval 279–575) premature deaths would be preventable annually, with 235 (174–359) premature deaths preventable in census tracts of lower socioeconomic status and 141 (10–216) premature deaths preventable in census tracts of higher socioeconomic status (p<0·0001; table 3). Census tracts with less than the median percent tree canopy cover in 2014 would benefit the most under this scenario.

The ambitious increase scenario, with a target of 30% total tree canopy cover, would increase tree canopy cover by 9·7% city-wide, 13·4% in census tracts of lower socioeconomic status, and 5·9% in census tracts of higher socioeconomic status (table 2). Because of unequal distribution of tree canopy coverage, populations in census tracts of lower socioeconomic status would benefit the most under this scenario. City-wide, 403 (95% interval 298–618) premature deaths could be prevented annually under this scenario, with 244 (180–373) premature deaths preventable in census tracts of lower socioeconomic status and 159 (11–244) premature deaths preventable in census tracts of higher socioeconomic status (p<0·0001; table 3). Achieving the 30% tree canopy cover by 2025 could help Philadelphia reduce annual premature mortality by 2·9% (95% interval 2·1–4·5) across the city. Tracts with less than the median percent tree canopy cover in 2014 would benefit the most under this scenario.

The estimated decreases in annual premature deaths translate to a value of approximately $2·9 billion (95% interval 2·1–4·4 billion) for the low increase scenario and $3·6 billion (2·7–5·5) for the moderate increase scenario (table 3). With the ambitious scenario, the value is nearly $3·9 billion (95% interval 2·9–5·9) in savings based on the projected VSL city-wide, $2·3 billion (1·7–3·6) in census tracts of lower socioeconomic status and $1·5 billion (1·1–2·3) in census tracts of higher socioeconomic status.

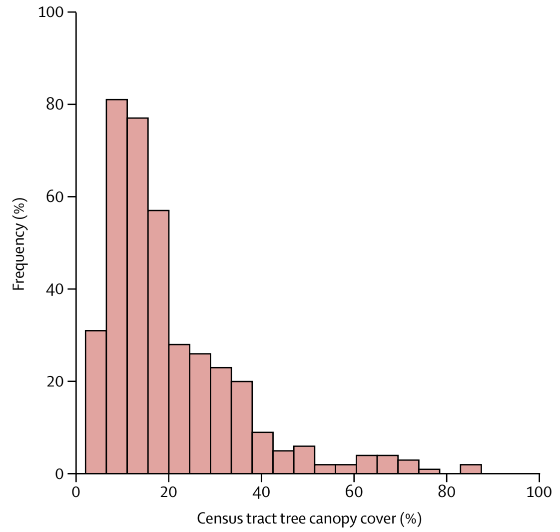

Figure 2: **Frequency of census tract tree canopy cover**
Based on 2014 landcover data.

	Projected tree canopy increase, 2014–2025 (%)
Low increase scenario*	
City-wide	3·7%
Lower socioeconomic status census tracts	4·5%
Higher socioeconomic status census tracts	2·9%
Moderate increase scenario†	
City-wide	7·4%
Lower socioeconomic status census tracts	8·8%
Higher socioeconomic status census tracts	6·0%
Ambitious increase scenario‡	
City-wide	9·7%
Lower socioeconomic status census tracts	13·4%
Higher socioeconomic status census tracts	5·9%

*Five percentage point increase in tree canopy coverage. †Ten percentage point increase in tree canopy coverage. ‡30% total tree canopy cover.

Table 2: **Average projected percent tree canopy cover change (2014–2025), by census tract, socioeconomic status, and scenario**

	Preventable premature adult deaths		Value (millions, US$ 2015 [95% interval])*
	n (95% interval)	% (95% interval)	
Low increase scenario†			
City-wide	302 (223–461)	2·2% (1·6–3·3)	2895 (2149–4431)
Lower socioeconomic status census tracts	190 (140–289)	2·7% (2·0–4·1)	1820 (1351–2783)
Higher socioeconomic status census tracts	112 (83–171)	1·6% (1·2–2·4)	1076 (798–1647)
Tree canopy cover (%)			
Quantile 1 (<10%)	87 (64–133)	2·6% (1·9–4·0)	837 (621–1281)
Quantile 2 (12–15%)	96 (71–147)	3·0% (2·2–4·6)	926 (687–1417)
Quantile 3 (16–26%)	77 (57–117)	2·0% (1·4–3·0)	741 (550–1131)
Quantile 4 (>27%)	41 (3–62)	1·1% (0·8–1·7)	391 (289–599)
Moderate increase scenario‡			
City-wide	376 (279–575)	2·7% (2·0–4·2)	3609 (2678–5528)
Lower socioeconomic status census tracts	235 (174–359)	3·5% (2·5–5·3)	2254 (1672–3452)
Higher socioeconomic status census tracts	141 (10–216)	2·1% (1·5–3·1)	1355 (1005–2076)
Tree canopy cover (%)			
Quantile 1 (<10%)	162 (120–248)	4·9% (3·6–7·5)	1555 (1152–2386)
Quantile 2 (12–15%)	127 (94–195)	4·0% (2·9–6·1)	1223 (907–1873)
Quantile 3 (16–26%)	77 (57–117)	2·0% (1·4–3·0)	738 (548–1126)
Quantile 4 (>27%)	10 (7–14)	0·3% (0·2–0·4)	94 (69–142)
Ambitious increase scenario§			
City-wide	403 (298–618)	2·9% (2·1–4·5)	3865 (2865–5933)
Lower socioeconomic status census tracts	244 (180–373)	3·6% (2·6–5·5)	2339 (1735–3586)
Higher socioeconomic status census tracts	159 (11–244)	2·4% (1·7–3·6)	1526 (1130–2346)
Tree canopy cover (%)			
Quantile 1 (<10%)	196 (144–301)	5·9% (4·3–9·1)	1877 (1389–2890)
Quantile 2 (12–15%)	129 (95–197)	4·0% (2·9–6·1)	1235 (916–1891)
Quantile 3 (16–26%)	75 (55–113)	1·9% (1·4–2·9)	716 (532–1092)
Quantile 4 (>27%)	3 (2–4)	0·1% (0·0–0·1)	28 (2–43)

*Based on value of a statistical life year for 2015 generated by the US Department of Transportation; values are per million (2015 $US). †Five percentage point increase in tree canopy coverage. ‡Ten percentage point increase in tree canopy coverage. §30% total tree canopy cover.

Table 3: **Annual preventable premature adult deaths (2014–2025) and economic effects**

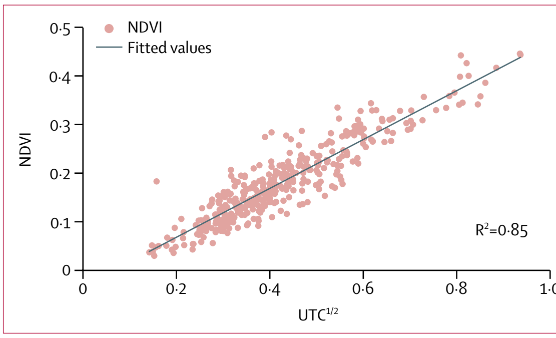

Figure 3: **Scatterplot of 2014 NDVI scores versus tree canopy cover values**
NDVI=Normalized Difference Vegetation Index. UTC=percent of pixels within each census tract that were tree canopy.

Discussion

To the best of our knowledge, our report is the first city-wide health impact assessment of estimated effects of a tree canopy policy on premature mortality. Using our greenspace health impact assessment method, we predicted annual premature deaths prevented from increased tree canopy cover (throughout the city, on public and private lands) under low, moderate, and ambitious scenarios. We were able to do this assessment because of the good relation between tree canopy cover and NDVI in Philadelphia, which allowed us to use NDVI as a surrogate for tree cover and tree canopy policy goals (figure 3). The results are considerable: a five percentage point increase in tree canopy only in areas containing non-tree vegetation could result in an annual reduction of 302 deaths city-wide, which translates to a value of $2·9 billion based on projected VSL. A ten percentage point increase in tree canopy cover across the city was associated with an estimated reduction of 376 deaths, and $3·6 billion. 403 premature adult deaths (3% of total mortality) could potentially be prevented annually if Philadelphia accomplished its goal of increasing tree canopy cover to 30% by 2025, as set forth in the Greenworks Philadelphia plan. The predicted value associated with these averted deaths was nearly $3·9 billion.

Census tracts of lower socioeconomic status would benefit the most from increases in tree canopy coverage. Although consensus does not exist in published work,[10,36] our conclusion is based on the assumption that the exposure–response function is the same for all socio-economic status strata. Under the moderate and ambitious increase scenarios, areas of the city with lower than median percent tree canopy cover would benefit the most, whereas under the low increase scenario, areas of the city with the 50–70th percentile of tree canopy cover would see most benefit. This difference could be attributable to the fact that plantable space is constrained in neighbourhoods with low tree canopy cover and a greater amount of impervious surfaces (eg, neighbourhoods with little to no residential lawn space).

The effects recorded would benefit residents of Philadelphia and other similar cities. Philadelphia has higher rates of mortality compared with the US population. Moreover, according to Philadelphia's Department of Public Health, 9071 life-years were lost to mortality of all causes for all residents younger than 75 years in 2015. After a steady decline, this number began to increase in 2015.[37] Although cancer and heart disease were the top causes of death, the increase was probably attributable to drug overdoses and youth homicide.[22] Since the dose–response relation is derived from counts of all-cause mortality, we cannot estimate which causes of death the tree canopy cover increase would directly affect. However, we can postulate (based on previous studies) that pathways include social cohesion or engagement, stress or mental health, physical activity, and reduction in heat island effects.[10,38,39] Experimental and quasi-experimental work in Philadelphia has shown that greening interventions throughout the city led to improved mental health outcomes[40] and reduced drug crime[41] and gun violence.[42]

Although we can predict economic values associated with prevented loss of life using the VSL, we were not able to compare the costs and benefits of increasing tree canopy directly. Predicted values do not correspond to direct costs or cost savings assumed by any one entity, such as the city. Moreover, it is very difficult to estimate cost for tree canopy goals because of many uncertainties, eg, related to unknown losses to development or natural causes. Health benefits can also come from greening interventions other than tree planting (eg, landscaping or gardens). Few, if any, experimental studies have compared the effects of tree planting versus other forms of greening or public health interventions on morbidity or mortality. However, for a gross comparison, jurisdictions with active urban forestry programmes in Pennsylvania spent an estimated $5·21 per person in 2017 on urban forestry management in general,[43] whereas the 2017 obligations for Philadelphia's public health department was nearly $133 million, or $84·1 per person.

Practical and programmatic limitations could reduce the projected effects of a tree planting programme. To meet the 30% tree canopy cover target, tree planting programmes will need to target not only publicly managed spaces (eg, streets and parks) but also residential yards and other privately owned commercial, industrial, or institutional spaces. Philadelphia and other cities do have such programmes,[2,20] but implementation challenges remain, for example with gaining participation and long-term stewardship from residents.

Tree canopy cover is sometimes constrained by limited space in densely populated, older (and typically poorer) areas.[44,45] Yet, Philadelphia's tree canopy goal emphasises it is for all neighbourhoods, and the city is taking measures to reduce the disparity in tree canopy cover, for example via neighbourhood partnerships in planting programmes.[2] Furthermore, tree canopy goals, similar to our scenario build-outs, generally assume that tree canopy cover is steady and will only increase over time. However, urban forests are dynamic,[45] with trees constantly added and removed.[46] Preservation of existing tree canopy and support for new canopy relies on municipal tree ordinances, and enforcement of strong ordinances is absent in Philadelphia.[47] Cities can also experience rapid drops in tree cover because of extreme weather events, invasive pests, and diseases.[45] These rapid drops can be unpredictable, making planning and budgeting for increases in net tree cover a challenge for cities.

Because of the disparity in current distribution of Philadelphia's tree canopy cover, the biggest health benefits were estimated to occur within areas of lower socioeconomic status. Urban forestry programmes rarely achieve equitable distribution of trees across a city,[44] although Philadelphia's residential yard tree programme shows more equitable distribution than others.[2] Affluent neighbourhoods generally have more tree cover and planting initiatives.[44,48] In poor communities, greening programmes can signify gentrification and eventual displacement.[49] Residents might also dislike trees because of a previous absence of municipal maintenance.[50] Trees come with management costs and safety liabilities that can cause residents to resist planting or to remove unwanted trees.[51] Yet urban greening initiatives that target disadvantaged neighbourhoods, as long as they do not displace residents, could help reduce health inequalities.[49] Although further research is needed to assess whether trees contribute to displacement, tree planting in poor neighbourhoods might need to be coupled with additional programmes and policies to maintain neighbourhood economic diversity, for example preserving affordable housing and assisting tenants at risk of displacement.[52]

Our use of meta-estimates of relative risk has some limitations. Because of the paucity of individual-level data, we had to apply the exposure–response estimate at the census tract level. The estimate by Rojas-Rueda and colleagues[13] is based on studies in which greenspace exposure represented mean NDVI within 500 m of residential location rather than within census tract of residence. However, the mean census tract area in our study was 81 hectares, which is not entirely different from the 500 m buffer.[53]

Our use of NDVI data also has limitations. Estimates of the association between greenspace exposure and mortality have relied on imprecise exposure measurements. For example, NDVI (often at 30 m or larger resolution) can also be a coarse measure of greenspace exposure[18] and is a poor measure of the quality of trees or greenspace. Unhealthy, dead, or dying trees can register as vegetation but might detract from community wellbeing. NDVI also does not convey accessibility of greenspace. Moreover, greenspace exposure, as represented by residential NDVI, could encompass multiple mechanisms of effect on health outcomes. A different study design would be needed to ascertain the relation between health and specific design features or planning elements. Although more precise and standardised exposure measurements are needed, NDVI remains the best and most widely available greenspace exposure metric for large-scale longitudinal cohort and population-level studies.

Most studies, including ours, apply a single VSL estimate; however, VSL can be affected by various sociodemographic factors, such as wealth, age, and health status.[33] For example, VSL is predicted to increase with higher wealth and can be affected by baseline risk of premature mortality. However, in our study we applied a single generalised estimate and calculated economic value associated with prevented premature mortality associated with varying levels of projected change in tree canopy, and how this estimate varies by socioeconomic position of neighbourhoods.

Although mortality is an extreme event, we did not consider potential effects on morbidity (eg, mental health) and wellbeing. Many established benefits are associated with a robust urban tree canopy, ranging from aesthetics to ecosystem services, temperature or thermal benefits, noise pollution mitigation, and social interactions.[38,54,55] Policymakers are warranted in viewing urban tree canopy preservation and expansion as one tool, aside from more traditional measures, to promote health and reduce health-care-related costs.

In our study we used a dose–response function from a meta-analysis[13] of cohort studies based on data from more than 7 million participants. Our study is unique in that it provides estimates for areas of high and low socioeconomic status. This approach can be applied in other cities with greening initiatives, where landcover data exist and fine-scale death records are published.

In Philadelphia, increases in tree canopy cover were estimated to provide considerable health and economic benefits. Residents of neighbourhoods of lower socioeconomic status are currently exposed to lower NDVI values (ie, fewer trees) than are residents of neighbourhoods of higher socioeconomic status and, therefore, were estimated to have a larger mortality burden. Thus, increases in tree canopy cover, particularly in neighbourhoods of lower socioeconomic status, could provide sizable benefits. Urban greening programmes can be a means, aside from traditional measures, to promote public health, decrease health inequalities, and promote environmental justice.

Contributors

MCK, MJN, and NM had the idea for the study and designed the analytical methods. MCK did all data analyses and wrote the report. MCK, NM, DHL, LAR, DR-R, LHS, MG, and MJN contributed to data interpretation and review and revision of the report.

Declaration of interests

We declare no competing interests.

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References

1 Young RF, McPherson EG. Governing metropolitan green infrastructure in the United States. *Landsc Urban Plan* 2013; **109:** 67–75.
2 Nguyen VD, Roman LA, Locke DH, et al. Branching out to residential lands: missions and strategies of five tree distribution programs in the US. *Urban For Urban Green* 2017; **22:** 24–35.
3 Steenberg JWN, Millward AA, Nowak DJ, Robinson PJ. A conceptual framework of urban forest ecosystem vulnerability. *Environ Rev* 2017; **25:** 115–26.
4 Jenerette GD. Ecological contributions to human health in cities. *Landsc Ecol* 2018; **33:** 1655–68.
5 Young R. Mainstreaming urban ecosystem services: a national survey of municipal foresters. *Urban Ecosyst* 2013; **16:** 703–22.
6 Nieuwenhuijsen MJ, Khreis H, Triguero-Mas M, Gascon M, Dadvand P. Fifty shades of green. *Epidemiology* 2017; **28:** 63–71.
7 Yasuda K. Priorities for 2019 focus on health of children and physicians. Jan 2, 2019. https://www.aappublications.org/news/2019/01/02/letter010219 (accessed March 11, 2020).
8 Kondo MC, Fluehr JM, McKeon T, Branas CC. Urban green space and its impact on human health. *Int J Environ Res Public Health* 2018; **15:** 445.
9 Wilker EH, Wu C-D, McNeely E, et al. Green space and mortality following ischemic stroke. *Environ Res* 2014; **133:** 42–48.
10 James P, Hart JE, Banay RF, Laden F. Exposure to greenness and mortality in a nationwide prospective cohort study of women. *Environ Health Perspect* 2016; **124:** 1344–52.
11 Gascon M, Triguero-Mas M, Martínez D, et al. Residential green spaces and mortality: a systematic review. *Environ Int* 2016; **86:** 60–67.
12 Twohig-Bennett C, Jones A. The health benefits of the great outdoors: a systematic review and meta-analysis of greenspace exposure and health outcomes. *Environ Res* 2018; **166:** 628–37.
13 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.
14 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.
15 Reid CE, Clougherty JE, Shmool JLC, Kubzansky LD. Is all urban green space the same? A comparison of the health benefits of trees and grass in New York City. *Int J Environ Res Public Health* 2017; **14:** E1411.
16 Jenerette GD, Harlan SL, Buyantuev A, et al. Micro-scale urban surface temperatures are related to land-cover features and residential heat related health impacts in Phoenix, AZ USA. *Landsc Ecol* 2016; **31:** 745–60.
17 Astell-Burt T, Mitchell R, Hartig T. The association between green space and mental health varies across the lifecourse: a longitudinal study. *J Epidemiol Community Health* 2014; **68:** 578–83.
18 Locke DH, Romolini M, Galvin M, O'Neil-Dunne JP, Strauss EG. Tree canopy change in coastal Los Angeles, 2009–2014. *Cities Environ* 2017; **10:** 3.
19 Raciti S. Urban tree canopy goal setting: a guideline for Chesapeake Bay communities. June 4, 2015. https://www.chesapeakebay.net/what/publications/urban_tree_canopy_goal_setting_a_guideline_for_chesapeake_bay_communities (accessed March 11, 2020).
20 Leahy I. Why we no longer recommend a 40 percent urban tree canopy goal. Jan 12, 2017. https://www.americanforests.org/blog/no-longer-recommend-40-percent-urban-tree-canopy-goal/ (accessed March 19, 2020).
21 US Census Bureau. 2011–2015 ACS 5-year estimates. June 7, 2019. https://www.census.gov/programs-surveys/acs/technical-documentation/table-and-geography-changes/2015/5-year.html (accessed March 11, 2020).
22 City of Philadelphia Department of Public Health. Vital statistics report: Philadelphia—2015. Nov 5, 2018. https://www.phila.gov/media/20181105161054/2015_Vital_Statistics_Report.pdf (accessed March 11, 2020).
23 Chesapeake Conservancy. Land cover data project 2013/2014. March 6, 2017. https://chesapeakeconservancy.org/conservation-innovation-center-2/high-resolution-data/land-cover-data-project/ (accessed March 19, 2020).
24 O'Neil-Dunne J. Tree canopy change in the City of Baltimore: 2007–2015. Aug 28, 2017. https://www.nrs.fs.fed.us/urban/utc/local-resources/downloads/BaltimoreTreeCanopyChange2007-2015.pdf (accessed March 11, 2020).
25 O'Neil-Dunne J. A report on the City of New York's existing and possible tree canopy. May 18, 2012. http://www.fs.fed.us/nrs/utc/reports/UTC_NYC_Report_2010.pdf (accessed March 11, 2020).
26 O'Neil-Dunne JP, MacFaden SW, Royar AR, Pelletier KC. An object-based system for LiDAR data fusion and feature extraction. *Geocarto Int* 2013; **28:** 227–42.
27 O'Neil-Dunne J. A report on the City of Philadelphia's existing and possible tree canopy. March 18, 2011. https://www.fs.fed.us/nrs/utc/reports/UTC_Report_Philadelphia.pdf (accessed March 11, 2020).
28 Pearsall H, Christman Z. Tree-lined lanes or vacant lots? Evaluating non-stationarity between urban greenness and socio-economic conditions in Philadelphia, Pennsylvania, USA at multiple scales. *Appl Geogr* 2012; **35:** 257–64.
29 ESRI. Landsat 8 (NDVI). Dec 13, 2019. https://www.arcgis.com/home/item.html?id=a1c373b16db34ef687ddae7c482e0b27 (accessed March 11, 2020).

30 NASA Earth Observatory. Measuring vegetation (NDVI & EVI). Aug 30, 2000. https://earthobservatory.nasa.gov/features/MeasuringVegetation/measuring_vegetation_2.php (accessed March 11, 2020).

31 Murray CJL, Ezzati M, Lopez AD, Rodgers A, Vander Hoorn S. Comparative quantification of health risks: conceptual framework and methodological issues. *Popul Health Metr* 2003; **1:** 1.

32 Schelling TC. The life you save may be your own. In: Chase SB, ed. Problems in public expenditure analysis: studies of government finance. Washington: The Brookings Institution, 1968: pp 127–76.

33 Andersson H, Treich N. The value of a statistical life. In: de Palma A, Lindsey R, Quinet E, Vickerman R, eds. A handbook of transport economics. Cheltenham: Edward Elgar Publishing, 2011: pp 396–424.

34 Russell LB. Do we really value identified lives more highly than statistical lives? *Med Decis Making* 2014; **34:** 556–59.

35 US Department of Transportation. Guidance on treatment of the economic value of a statistical life (VSL) in US Department of Transportation analyses, March 1, 2013. https://www.transportation.gov/regulations/guidance-treatment-economic-value-statistical-life-us-department-transportation-analyses (accessed March 11, 2020).

36 Vienneau D, de Hoogh K, Faeh D, et al. More than clean air and tranquillity: residential green is independently associated with decreasing mortality. *Environ Int* 2017; **108:** 176–84.

37 City of Philadelphia Department of Public Health. Health of the City 2018. Jan 10, 2019. https://www.phila.gov/media/20190110163926/Health_of_City_2018_revise2.pdf (accessed March 11, 2020).

38 Hartig T, Mitchell R, De Vries S, Frumkin H. Nature and health. *Annu Rev Public Health* 2014; **35:** 207–28.

39 Schinasi LH, Benmarhnia T, De Roos AJ. Modification of the association between high ambient temperature and health by urban microclimate indicators: a systematic review and meta-analysis. *Environ Res* 2018; **161:** 168–80.

40 South EC, Hohl BC, Kondo MC, MacDonald JM, Branas CC. Effect of greening vacant land on mental health of community-dwelling adults: a cluster randomized trial. *JAMA Netw Open* 2018; **1:** e180298.

41 Kondo MC, Low SC, Henning J, Branas CC. The impact of green stormwater infrastructure installation on surrounding health and safety. *Am J Public Health* 2015; **105:** e114–21.

42 Branas CC, South E, Kondo MC, et al. Citywide cluster randomized trial to restore blighted vacant land and its effects on violence, crime, and fear. *Proc Natl Acad Sci USA* 2018; **115:** 2946–51.

43 Environmental Finance Center at the University of Maryland, Alliance for the Chesapeake Bay. Financing urban tree canopy programs: guidebook for local governments in the Chesapeake Bay Watershed. March, 2019. http://chesapeaketrees.net/wp-content/uploads/2019/04/FinancingUrbanTreeCanopyPrograms_LowRes_040919.pdf (accessed March 11, 2020).

44 Locke DH, Grove JM. Doing the hard work where it's easiest? Examining the relationships between urban greening programs and social and ecological characteristics. *Appl Spat Anal Policy* 2016; **9:** 77–96.

45 Roman LA, Pearsall H, Eisenman TS, et al. Human and biophysical legacies shape contemporary urban forests: a literature synthesis. *Urban For Urban Green* 2018; **31:** 157–68.

46 Roman LA. How many trees are enough? Tree death and the urban canopy. https://scenariojournal.com/article/how-many-trees-are-enough/ (accessed March 11, 2020).

47 Hilbert DR, Koeser AK, Roman LA, et al. Development practices and ordinances predict inter-city variation in Florida urban tree canopy coverage. *Landsc Urban Plan* 2019; **190:** 103603.

48 Gerrish E, Watkins SL. The relationship between urban forests and income: a meta-analysis. *Landsc Urban Plan* 2018; **170:** 293–308.

49 Wolch JR, Byrne J, Newell JP. Urban green space, public health, and environmental justice: The challenge of making cities 'just green enough'. *Landsc Urban Plan* 2014; **125:** 234–44.

50 Carmichael CE, McDonough MH. Community stories: explaining resistance to street tree-planting programs in Detroit, Michigan, USA. *Soc Nat Resour* 2019; **32:** 588–605.

51 Conway TM. Tending their urban forest: residents' motivations for tree planting and removal. *Urban For Urban Green* 2016; **17:** 23–32.

52 New York University Furman Center. Gentrification response: a survey of strategies to maintain neighborhood economic diversity. October, 2016. https://furmancenter.org/files/NYUFurmanCenter_GentrificationResponse_26OCT2016.pdf (accessed March 11, 2020).

53 Schinasi L, Quick H, De Roos A, Clougherty J. Green space and infant mortality in Philadelphia, PA. *J Urban Health* 2019; **96:** 497–506.

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

55 Jennings V, Bamkole O. The relationship between social cohesion and urban green space: an avenue for health promotion. *Int J Environ Res Public Health* 2019; **16:** 452.