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The association between tree planting and mortality: A natural experiment and cost-benefit analysis

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ABSTRACT

Several recent longitudinal studies have found that exposure to the natural environment is associated with lower non-accidental mortality. However, most of these studies used the normalized difference vegetation index (NDVI) as an exposure metric; and because NDVI might not be sensitive enough to adequately capture changes in urban vegetation, these studies might lack true longitudinal variation in exposure. Therefore, we used a natural experiment to assess the impact of 30 years of tree planting by the nonprofit Friends of Trees on non-accidental, cardiovascular, lower-respiratory, and accidental mortality in Portland, Oregon (mortality data were provided by the Oregon Health Authority). We estimated autoregressive mixed models of Census-tract level mortality rate (deaths per 100,000 population) associated with trees planted, including a tract-level random effect. All models used data from the American Community Survey to control for year, race, education, income, and age. Each tree planted in the preceding 15 years was associated with significant reductions in non-accidental (-0.21, 95 % CI: −0.30, −0.12) and cardiovascular mortality (-0.065, 95 % CI: −0.11, −0.027). Furthermore, the dose–response association between tree planting and non-accidental mortality increased in magnitude as trees aged and grew. Each tree planted in the preceding 1–5 years was associated with a reduction in mortality rate of −0.154 (95 % CI −0.323, 0.0146), whereas each tree planted in the last 6–10 and 11–15 years was associated with a reduction in mortality rate of −0.262 (95 % CI: −0.413, −0.110) and −0.306 (95 % CI: −0.527, −0.0841) respectively. Using US EPA estimates of a value of a statistical life, we estimated that planting a tree in each of Portland's 140 Census tracts would generate $14.2 million in annual benefits (95 % CI: $8.0 million to $20.4 million). In contrast, the annual cost of maintaining 140 trees would be $2,716–$13,720.

1. Introduction

Evidence from longitudinal studies provides support for a consistent association between exposure to the natural environment and lower all-cause mortality (Chen et al., 2020; Crouse et al., 2017; de Keijzer et al., 2017; Hu et al., 2008a; Hyam, 2020; James et al., 2016; Ji et al., 2019; Kasdagli et al., 2021; Kim et al., 2019; Kua and Lee, 2021; Lee et al., 2020; Orioli et al., 2019; Sun et al., 2020; Yitshak-Sade et al., 2019). Although these studies collectively strengthen the evidence that exposure to the natural environment may reduce mortality, they share a methodological limitation: limited longitudinal variation in exposure. The reason for this is twofold. First, in most locations, the natural environment only changes slowly over time (Kline et al., 2007). Second, most extant longitudinal studies use the normalized difference vegetation index (NDVI) as an exposure metric, and NDVI is derived from satellite imagery and might not be sensitive enough to detect the changes that do occur (Gascon et al., 2016). In addition, NDVI is nonspecific; it can't distinguish between different types of vegetation with the same photosynthetic activity

We address the limitations of the extant literature by taking

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advantage of a natural experiment to study the impact of tree planting on mortality. Specifically, we make use of data from the nonprofit Friends of Trees, which planted 49,246 street trees in Portland, Oregon from 1990 to 2019 (street trees are planted in the green strip between the sidewalk and the road). Unlike studies that use NDVI as an exposure metric, this study looks at the number of trees planted in a location—a measure that exhibits major longitudinal variation. In addition, the planting data capture small changes in exposure—the planting of a single tree—that may not be captured by NDVI. Finally, in contrast to increases in NDVI, tree planting is a specific intervention that can be easily applied in practice.

1.1. *Literature review*

Several ecological longitudinal studies have found that exposure to higher levels of greenness is associated with lower non-accidental mortality (de Keijzer et al., 2017; Hu et al., 2008b; Hyam, 2020; Kasdagli et al., 2021; Kim et al., 2019; Lee et al., 2020). Some of these studies also reported that exposure to greenness was associated with lower cardiovascular (Hu et al., 2008b; Kim et al., 2019; Lee et al., 2020) and respiratory mortality (Lee et al., 2020). In addition, a number of the studies reported that exposure to greenness attenuated the association between air pollution and mortality, although the direction of these interactions was not always consistent (de Keijzer et al., 2017; Kim et al., 2019). Finally, two studies reported that the protective association between greenness and mortality was higher for certain demographic groups—specifically urban residents (Kasdagli et al., 2021) and residents of areas with lower socioeconomic status (SES) (de Keijzer et al., 2017).

Several longitudinal cohort studies have also reported that exposure to greenness is associated with lower non-accidental (Chen et al., 2020; Crouse et al., 2017; James et al., 2016; Ji et al., 2019; Orioli et al., 2019; Sun et al., 2020; Vienneau et al., 2017; Yitshak-Sade et al., 2019), cardiovascular (Chen et al., 2020; Crouse et al., 2017; Orioli et al., 2019; Vienneau et al., 2017; Yitshak-Sade et al., 2019), and respiratory mortality (Sun et al., 2020; Vienneau et al., 2017). A number of these studies reported that the magnitude of the association between greenness and longevity was greater for people with higher SES (Crouse et al., 2019; de Keijzer et al., 2017). Finally, several studies reported significant interactions between greenness and air pollution; however, as with ecological studies, the sign of these interactions was sometimes inconsistent (Orioli et al., 2019; Yitshak-Sade et al., 2019).

Two recent *meta*-analyses examined the relationship between greenness and non-accidental mortality. Kua et al. (2021) included five cohort studies conducted in the Asia-Pacific region. They found that the pooled hazard ratio (HR) associated with a 0.1-point increase in NDVI within 500 m of residential address was 0.96 (95 % CI: 0.93–1.02). Rojas-Rueda et al. (2019) included nine studies in their analysis (seven of which found a significant association between greenness exposure and reduced mortality). The pooled HR of a 0.1-point increase in NDVI within 500 m of residential address was 0.96 (95 % CI: 0.94–0.97).

Two longitudinal studies took a fundamentally different approach to evaluating the relationship between greenness and mortality. Rather than use NDVI-based exposure metrics, these studies quantified the impact of tree loss from an invasive tree pest (the emerald ash borer) on mortality. One ecological study found that tree loss was a risk factor for cardiovascular and lower-respiratory mortality (Donovan et al., 2013), while a cohort study found that tree loss was a risk factor for cardiovascular disease (Donovan et al., 2015).

2. Materials and methods

2.1. *Data and study area*

2.1.1. *Mortality data*

Mortality data were observed annually at the Census-tract level from 2006 to 2019. The mean population of a tract was 4,318 (SD = 1,700), and the mean size was 226 ha (SD = 422). We used this sample frame, as, before 2006, the Oregon Health Authority reported data by zip code rather than tract. Deaths were included in the analysis if the decedent lived in one of the 140 Census tracts in Portland, Oregon (we included a tract in the analysis if > 50 % of its area was within the city limits) and the death occurred in the state of Oregon. We considered three causes of death: cardiovascular (ICD10: I00.0–I78.9), chronic lower respiratory (ICD10: J40.0–J47.9), and accidental (ICD10: V01–X59, Y85–Y86). In addition, we considered non-accidental mortality, which we categorized as all mortality minus accidental deaths. We chose these categories of mortality because most extant studies of greenness and mortality focused on non-accidental mortality. In addition, past studies have found an association between trees and cardiovascular and lower-respiratory disease and used accidental death as a negative control (Donovan et al., 2013; Donovan et al., 2015). Finally, cause-specific mortality data were additionally stratified by sex and by age (<65 versus ≥65).

2.1.2. *Tree-planting data*

We used tree-planting records from Friends of Trees, which is a Portland-based nonprofit. Between 1990 and 2019, Friends of Trees planted 49,246 street trees in Portland. Depending on species, trees were four to eight years old when planted. We focused on street trees for three reasons. First, compared to trees planted in private gardens, street trees are a uniquely visible type of tree that, *a priori*, we would expect to have a broader neighborhood-level impact on health. Second, in Portland, planting a street tree requires a permit, so we know how many trees were planted (in contrast, planting a tree on private property does not require a permit). Third, street trees can be planted by government agencies and non-profits, so they are more relevant from a public-policy perspective.

Friends of Trees plants trees in two main ways. First, they organize neighborhood-level tree planting events: the residents of a neighborhood get together on a single day and collectively plant trees. These planting events are focused on underserved neighborhoods that have few trees. Friends of Trees will also provide trees to individual residents who request them. These requests are more likely to come from residents of more affluent neighborhoods with above average tree canopy. The combined effect of these two mechanisms is that trees planted by Friends of Trees are uncorrelated with existing tree canopy cover (correlation coefficient = −0.232).

A priori, we would not expect a small, recently planted sapling to provide the same health benefits as a mature tree. Therefore, to assess whether the association between trees and mortality changed as trees aged and grew, for each tract and year, we calculated the number of trees planted in the preceding 15 years as well as in three tree-age bands: 1–5 years, 6–10 years, and 11–15 years after planting.

2.1.3. *Covariates*

To control for demographic drivers of mortality that may confound the association of interest, we used data from the US Census's American Community Survey (US Census, 2019). Specifically, we assigned the midpoint of five-year estimates to individual years—we used 2015–2019 estimates for 2017, for example (Manson et al., 2021). ACS 5-year estimates were not available for 2006 and 2019, so we used values from 2007 and 2018, respectively, for these two years. Finally, we chose candidate variables, because past research had found them to be associated with mortality.

2.2. *Statistical analysis*

Our data were structured longitudinally, so we estimated linear mixed models of mortality rate including tract-level random effects:

$$MortalityRate_{i,j} = b_1 Trees_{i,j} + \mathbf{b}_2^{'} \mathbf{x}_{i,j} + \mathbf{b}_3^{'} \mathbf{Year} + \mu_j + \varepsilon_{i,j} \quad (1)$$

Where $MortalityRate_{i,j}$ denotes deaths per 100,000 of population in the *ith* year and the *jth* Census tract; $Trees_{i,j}$ denotes the number of trees planted in the *ith* year and the *jth* Census tract; $\mathbf{x}_{i,j}$ is a vector of covariates; **Year** is a vector containing 13 year-indicator variables (2006 excluded) that accounts for possible non-stationarity in mortality rates (we chose to represent time categorically to avoid an assumption of a linear relationship between mortality and year); μ_j is a tract-level random effect; $\varepsilon_{i,j}$ is an i.i.d. error term; and b_1, $\mathbf{b}_2$, $\mathbf{b}_3$, are parameters to be estimated.

Preliminary estimates of equation (1) revealed possible residual autocorrelation, implying that observed mortality rates within a tract may not be temporally independent, potentially making $\varepsilon_{i,j}$ not i.i.d. Therefore, we included a within-tract (AR(1)) autoregressive residual structure to account for this, i.e., $\varepsilon_{i,j} = \rho\varepsilon_{i-1,j} + \omega_{i,j}$ and $\omega_{i,j}\ N\left(0, \sigma_j^2\right)$, so that an estimate of equation (1) additionally includes an estimate of ρ. Finally, it is possible that mortality and tree planting are codetermined: tree planting may reduce mortality, but healthier people may be more likely to plant trees. To address this issue, we lagged the number of trees planted by at least one year (mortality in the current year was regressed against tree planting in the previous, or earlier, years). Lagging the planted trees avoids an inference of reverse causation, as mortality cannot causally influence the number of trees planted in previous years.

To determine if observed associations between tree planting and mortality were consistent across our sample, we estimated models stratified by sex, age (<65 versus ≥65), and existing tree cover (<26.1 % versus ≥26.1 %). In addition, we re-estimated our model of non-accidental mortality using NDVI as an exposure metric (as opposed to number of trees planted) to provide comparable results with previous studies. Specifically, we used data from Landsat 5, 7, and 8 to calculate mean NDVI for each tract (Gorelick et al., 2017). The NDVI value for each pixel was the maximum of multiple cloud-free scenes. Before calculating the mean value for a tract, all large bodies of water were removed. Finally, as a negative control, we estimated a model of accidental mortality (*a priori*, we would expect to find no association between tree planting and accidental mortality).

Past research has shown that broad demographic categories—income, race, education, and age—are associated with mortality risk. Therefore, our model-selection process involved identifying the variable within each of these categories that had the lowest p-value when regressed individually against mortality rate. For example, in the case of education, we chose between variables describing high-school graduation, having a bachelor's degree, and having a graduate degree. Even non-significant variables can be important confounders (Rothman et al., 2008), so we retained at least one variable from each demographic category, even if the variable wasn't significant. We next iteratively added other variables that did not fit within the four broad demographic categories and retained the variable if its p-value was <0.05. These variables included male unemployment rate, percent of households headed by a female, and percent of households that are renters.

3. Results

Table 1 shows descriptive statistics for the sample, and Fig. 1 shows the total number of street trees planted annually by Friends of Trees, which increased over time, peaked in 2012, and has modestly declined since. The number of trees planted by Friends of Trees in the last 15 years is mostly uncorrelated with demographic drivers of mortality such as income (correlation coefficient = 0.22), white residents (correlation coefficient = −0.068), housing tenure (correlation coefficient = −0.073), or residents with a bachelor's degree (correlation coefficient = 0.17). However, the number of trees planted in the last 15 years was modestly positively correlated with the percentage of black residents in a tract (correlation coefficient = 0.31), which reflects the focus of Friends of Trees on underserved communities.

The lack of correlation between tree planting and the demographic composition of a tract makes it less likely that models are subject to residual confounding by demographic determinants of mortality. This lack of correlation is important, as it means that it is unlikely that healthy people are choosing to move to neighborhoods in which more trees had been planted (self-selection bias).

Table 1
Means and standard deviation for select variables stratified by quartiles of the total number of trees planted in a Census tract (Q1 < 51; 227 > Q2 ≥ 51; 596 > Q3 ≥ 227; Q4 ≥ 596). Means and standard deviations were calculated across both Census tracts and time.

Variable	Q1: Mean [SD]	Q2: Mean [SD]	Q3: Mean [SD]	Q4: Mean [SD]
Non-accidental deaths (per 100,000)	[illegible]2 [361]	[illegible]98 [34[illegible]]	63[illegible] [305]	536 [185]
Major cardiovascular deaths (per 100,000)	183 [146]	244 [155]	186 [115]	153 [76.7]
Chronic lower-respiratory deaths (per 100,000)	32.5 [39.4]	46.9 [40.3]	33.3 [32.5]	28.8 [27.0]
Accidental deaths (per 100,000)	45.9 [51.6]	50.8 [43.2]	41.0 [38.0]	31.0 [28.[illegible]]
White (%)	84.8 [7.48]	74.3 [9.90]	77.7 [11.9]	77.7 [11.9]
African American (%)	3.53 [3.36]	5.80 [4.77]	8.[illegible] [8.54]	9.62 [9.63]
Age > 25 with bachelor's degree (%)	32.3 [7.[illegible]2]	16.6 [9.58]	26.9 [8.[illegible]1]	27.9 [6.10]
Median age	39.6 [5.92]	36.4 [3.57]	36.9 [4.20]	36.3 [3.89]
Median household income	76,850 [35,347]	47,287 [13,880]	62,988 [21,920]	67,668 [22,379]
Mean NDVI	0.495 [0.166]	0.443 [0.0[illegible]51]	0.4[illegible]2 [0.0577]	0.453 [0.0537]
Parks (%)	9.67 [13.9]	5.31 [8.46]	4.66 [5.25]	4.10 [5.4[illegible]]

Table 2 shows the association between non-accidental mortality rate and tree planting in the previous 15 years. Consistent with *a priori* expectations, both median household income and the proportion of the population with a bachelor's degree were negatively associated with non-accidental mortality. Also consistent with expectations, median age was positively associated with mortality. The coefficients on all year indicator variables were negative (although not all were significant), which shows that mortality rate trended unevenly downward over the study period. Finally, race (percent white) was not significantly associated with mortality rate. The AR(1) parameter, ρ, was significant, which suggests that mortality rate is temporally autoregressive.

The number of trees planted in the preceding 15 years was negatively and significantly associated with non-accidental mortality (Table 2). To calculate the mean annual reduction in deaths associated with tree planting, we multiplied the mean annual number of trees planted in a tract (11.7) by the coefficient on the number of trees planted in the last 15 years from Table 2 (−0.207) by the population of Portland in hundreds of thousands (6.44). Recall that mortality is per 100,000 in population. The associated annual reduction in deaths is 15.6 (95 % CI: 8.8–22.4).

Table 3 shows the association between non-accidental mortality and trees of different ages: 1–5 years, 6–10 years, and 11–15 years after planting. Results show that the magnitude of the association between trees and mortality increased as trees aged and grew. Specifically, the reduction in mortality associated with trees 11–15 years after planting was twice as large as the reduction in mortality associated with trees 1–5 years after planting.

Table 4 shows the association between cardiovascular mortality, lower-respiratory mortality, accidental mortality, and the number of trees planted in the preceding 15 years. We observed a negative association for CVD and lower-respiratory mortality, although only the association with CVD was statistically significant. Table 4 also shows that planting the mean number of trees per tract (11.7) was associated with

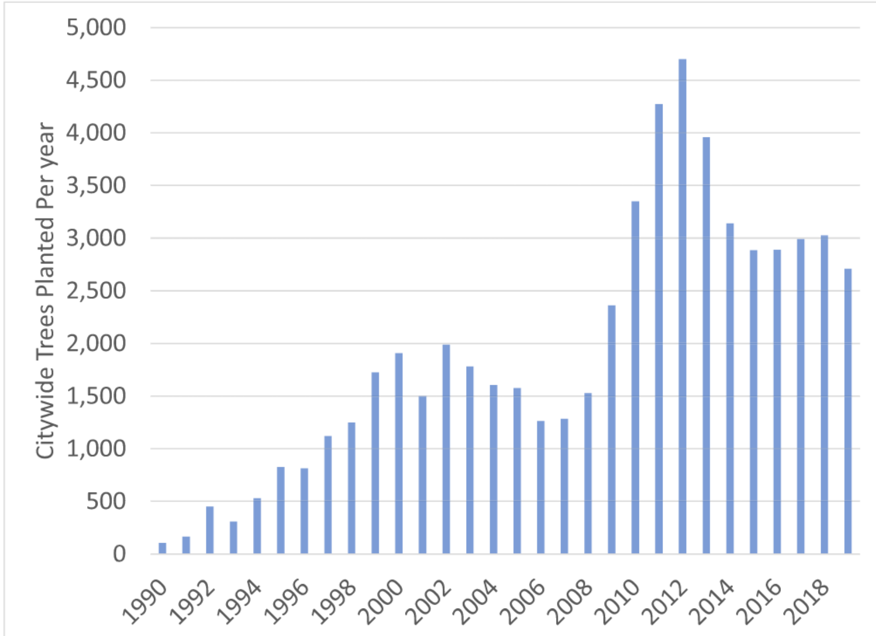

Fig. 1. Number of street trees planted annually by Friends of Trees in Portland, Oregon.

Table 2
The association between non-accidental mortality rate (per 100,000 population) and tree planting controlling for income, age, education, year, and race in Portland, Oregon 2006–2019 (# tracts = 140; # observations = 1,949).

Variable	Coefficient	p-value	Lower 95 % CI	Upper 95 % CI
# Trees planted (1–15 year lag)	−0.207	<0.001	−0.297	−0.117
Median household income ($)	−0.00205	<0.001	−0.00304	−0.00106
Median age	13.6	<0.001	8.55	18.7
Age > 25 with bachelor's degree (%)	−9.53	<0.001	−14.13	−4.9
White (%)	1.89	0.390	−2.42	6.20
Year (2006 excluded)				
2007	0.687	0.972	−37.1	38.5
2008	−37.5	0.045	−74.3	−0.761
2009	−58.8	0.001	−92.0	−25.5
2010	−93.4	<0.001	−131	−56.1
2011	−67.8	0.002	−110	−25.2
2012	−55.9	0.018	−102	−9.63
2013	−38.3	0.091	−82.8	6.16
2014	−83.1	0.001	−129	−37.4
2015	−56.0	0.014	−101	−11.5
2016	−70.3	0.004	−119	−22.0
2017	−44.8	0.095	−97.4	7.80
2018	−74.5	0.004	−125	−24.3
2019	−51.5	0.042	−101	−1.88
Tract-level variance	53,195		32,468	87,152
AR(1) parameter: ρ	0.195		0.115	0.272

an annual reduction of 5.0 (95 % CI: 1.9–8.0) CVD deaths. Association with lower respiratory deaths was statistically weak (10 % significance), while tree planting was not significantly associated with accidental mortality.

Table 5 shows how the association between tree planting and non-accidental mortality varied by sex, age, and existing tree cover. Specifically, tree planting is associated with greater reductions in male, as opposed to female, non-accidental mortality; and tree planting is more protective of non-accidental mortality in people who are 65 and over compared to those who are younger than 65. Finally, tree planting was associated with greater reductions in non-accidental mortality in tracts with above average existing tree cover, although this different was not significant (p = 0.89).

We found that NDVI was not significantly (p = 0.928) associated with non-accidental mortality (results not shown), which suggests that NDVI is not sensitive enough to capture the effect of tree planting in our sample. To confirm this, we examined the correlation between tract level changes in NDVI ($NDVI_{\Delta} = NDVI_{2019}$-$NDVI_{2006}$) with the total

Table 3
The association between non-accidental mortality rate (per 100,000 population) and tree planting in three age bands controlling for income, age, education, year, and race in Portland, Oregon 2006–2019 (# tracts = 140; # observations = 1,949).

Variable	Coefficient (95 % CI)	p-value	Deaths averted (95 % CI)[a]
Trees planted (1–5 year lag)	−0.154 (−0.323, 0.0146)	0.073	11.6 (−1.09, 24.4)
Trees planted (6–10 year lag)	−0.262 (−0.413, −0.110)	0.001	19.7 (8.28, 31.2)
Trees planted (11–15 year lag)	−0.306 (−0.527, −0.0841)	0.007	23.1 (6.35, 39.1)

[a] Deaths averted is the reduction in mortality associated with planting the mean annual number of trees per Census tract (11.7).

Table 4
The association between cardiovascular, lower-respiratory, and accidental mortality (per 100,000 population) and tree planting in the preceding 15 years controlling for income, age, education, year, and race in Portland, Oregon 2006–2019 (# tracts = 140; # observations = 1,949).

Variable	Coefficient (95 % CI)	p-value	Deaths averted (95 % CI)[a]
CVD (whole sample)	−0.0656 (−0.106, −0.0266)	0.001	4.95 (1.93, 7.98)
Lower respiratory (whole sample)	−0.00795 (−0.0173, 0.00140)	0.096	0.600 (−0.106, 1.31)
Accidental mortality (whole sample)	−0.0227 (−0.0543, 0.00902)	0.161	1.71 (−0.681, 4.10)

[a] Deaths averted is the reduction in mortality associated with planting the mean annual number of trees per Census tract (11.7).

Table 5
The association between tree planting in the preceding 15 years and non-accidental mortality (per 100,000 population) stratified by sex, age (<65 versus ≥65), and existing tree cover (<26.1 % versus ≥26.1 %) controlling for income, age, education, year, and race in Portland, Oregon 2006–2019 (# tracts = 140; # observations = 1,949).

Variable	Coefficient (95 % CI)	p-value	Deaths averted (95 % CI)[a]
Non-accidental (female)	−0.212 (−0.340, −0.0830)	0.001	15.0 (6.26, 25.7)
Non-accidental (male)	−0.291 (−0.402, −0.181)	<0.001	22.0 (13.7, 30.3)
Non-accidental (age < 65)	−0.0601 (−0.0979, −0.0223)	0.002	4.53 (1.68, 7.39)
Non-accidental (age ≥ 65)	−0.962 (−1.62, −0.301)	0.004	72.6 (22.7, 122)
Non-accidental (Tree cover < 26.1 %)	−0.211 (−0.106, −0.316)	<0.001	15.9 (7.98, 23.9)
Non-accidental (Tree cover ≥ 26.1 %)	−0.303 (−0.0780, −0.5270)	0.008	22.9 (5.89, 39.8)

[a] Deaths averted is the reduction in mortality associated with planting the mean annual number of trees per Census tract (11.7).

number of trees planted in a tract from 2006 to 2019. The correlation coefficient between the two was 0.29, which further suggests that NDVI, at least at 30 m resolution, is too coarse a metric to capture the effect of tree planting.

The potential reductions in mortality associated with tree planting can be achieved at modest cost. Specifically, a 2005 study (McPherson et al., 2005) estimated that the annual planting and maintenance costs of urban trees range from $12.87 to $65.00 per tree. Inflating these costs to 2022 dollars using the consumer price index gives a range of $19.40 to $98.00. For comparison, if we multiply the coefficient on tree planting in the last 1–15 years from Table 2 (−0.207) by the entire population of Portland (644,934, divided by 100,000 to account for the rate normalization), we see that planting one tree in each of Portland's 140 tracts is associated with an annual reduction in non-accidental death of 1.33 (95 % CI: 0.75–1.91). The US EPA values a statistical life at $10.7 million (US Environmental Protection Agency, 2022). Multiplying this value by the reduction in deaths from planting a tree in each tract, we get a value of $14.2 million (95 % CI: $8.0 million to $20.4 million). Using the costs referenced earlier, maintaining 140 trees, one in each tract, would cost just $2,716–$13,720 annually, <0.1 % of the statistical value of potential mortality averted. Moreover, these potential mortality benefits are in addition to the multiple well-documented co-benefits of trees (Roy et al., 2012).

4. Discussion

We found that tree planting in Portland, Oregon was significantly associated with reductions in non-accidental and cardiovascular mortality. Specifically, planting 11.7 trees in each tract (the mean annual number of trees planted in a tract) was associated with 15.6 (95 % CI: 8.8–22.4) fewer non-accidental deaths per year and 5.0 (95 % CI: 1.9–8.0) fewer deaths from CVD per year. We also found that as trees aged and grew, the magnitude of the association between tree planting and mortality increased. Furthermore, we found that tree planting had stronger inverse associations with male mortality (compared to female) and stronger inverse associations with mortality amongst people 65 and over (compared to those younger than 65). In addition, we found that the association between tree planting and mortality did not vary significantly between tracts with high versus low existing tree cover, which suggests that tree planting may provide health benefits in both green and less green neighborhoods. We did not find any association between NDVI and non-accidental mortality, which suggests that NDVI is too coarse of a metric to capture the impact of tree planting in our sample. We also found no association between tree planting and accidental mortality, which we used as a negative control. While not definitive, it is encouraging that tree planting was not associated with a cause of death it could not plausibly influence. Finally, we found that the magnitude of the mortality-reduction benefits associated with tree planting exceeded the costs by a factor of more than one thousand.

Our results are consistent with previous studies showing that exposure to higher residential greenness is associated with decreased mortality (Kua and Lee, 2021; Rojas-Rueda et al., 2019). However, these past studies that used NDVI as an exposure metric might not adequately capture longitudinal changes in the natural environment. Indeed, we found that changes in NDVI were not correlated with the number of trees planted in a tract. This lack of sensitivity is perhaps not surprising. The Nyquist-Shannon sampling theorem (Shannon, 1949), which originated in signal processing but is now a well-established norm in geospatial analysis and remote sensing, states that imagery can be effectively used to distinguish an object from its background if the size of the object is at least twice the resolution of the imagery. In the case of NDVI, most studies use 30 m Landsat imagery, and many elements of urban vegetation—individual trees, for example—are smaller than 60mX60m. Therefore, our findings provide important support for the extant literature. Specifically, using an exposure metric that was sensitive to small changes in greenness (the planting of a single tree), we found that longitudinal changes in greenness were associated with non-trivial reductions non-accidental mortality. Furthermore, we used an exposure metric that corresponds to a particular structural change in urban vegetation. Tree planting is something that can be readily specified as a simple, tractable public-health intervention. In contrast, NDVI could be increased in a wide range of ways, many of which might have quite different impacts on health. Finally, our finding that older trees are associated with larger decreases in mortality suggests that preserving existing mature trees may be particularly important for public health.

Our findings are also consistent with two studies showing that loss of trees to an invasive tree pest—the emerald ash borer—is associated with increases in cardiovascular and lower-respiratory mortality (Donovan et al., 2013; Donovan et al., 2015). Indeed, in combination with our current results, these studies provide stronger evidence of a causal link between trees and human mortality, because the evidence is symmetrical—loss of trees is accompanied by increases in mortality, whereas planting trees is associated with decreases in mortality.

Results do not provide any direct insight into the mechanisms linking tree planting and reductions in non-accidental mortality. However, our finding that larger trees are associated with greater reductions in mortality is consistent with several mechanisms. For example, as a tree grows, its leaf area increases, which also increases the ability of the tree to absorb air pollution (Nowak et al., 2006), moderate temperature (Jesdale et al., 2013), and dampen noise (Passchier-Vermeer and Passchier, 2000). In addition, across cultures, larger trees are aesthetically more appealing (Lohr and Pearson-Mims, 2006), so larger trees may be more psychologically restorative, and they may be more effective at promoting social cohesion. Finally, our findings are consistent with Chi et al. (2022), who found that exposure to larger trees in Brussels, Belgium, was associated with fewer prescriptions for cardiovascular disease and mood disorders.

4.1. Limitations

This study has several limitations. It is an observational study, so it cannot establish a causal relationship between trees and mortality. In addition, the tree-planting data we used did not account for all street trees planted in Portland. We only had comprehensive data on street tree planting from 2015 to 2019. During this period, trees planted by Friends of Trees represent 78 % of all street trees planted in Portland (the remaining 22 % were planted by individuals and government agencies). However, the number of trees planted by Friends of Trees and the number planted by others were uncorrelated (correlation coefficient = 0.177). If this lack of correlation was also the case for the rest of the study period, then failing to include other trees in our analysis likely did not bias coefficients of interest to a great degree, although the efficiency of coefficient estimates may have been reduced. Finally, we did not have any data on which trees died during the study period, nor did we have any information on tree species.

This is an ecological study (the observational units were tracts not individuals), so our findings may be subject to ecological bias, and we also didn't have any information on individual characteristics or how people interacted with the newly planted trees (how much time people spent outside, for example).

In addition, it is possible that healthier people prefer to live in neighborhoods with recent tree plantings, which could result in self-selection bias. However, we found that tree planting was not associated with housing tenure, which makes it unlikely that people are choosing to move into neighborhoods with recently planted trees. Moreover, research has found that pre-move health status is a relatively minor determinant of neighborhood choice (James et al., 2015). Finally, we did not consider the effect of tree planting in adjoining Census tracts.

During the 14-year study period, some people will have moved between tracts while others will have left the study area completely or moved into the study area from the outside. Such movement patterns may have biased coefficients of interest, increased equation variance, and in combination lowered the power of tests of statistical significance. Despite these limitations, we identified significant associations between non-accidental mortality and tree planting, providing important support for the extant literature showing that exposure to the natural environment may be protective of non-accidental mortality.

5. Conclusions

Tree planting in Portland, Oregon is associated with decreases in non-accidental and cardiovascular mortality, and the magnitude of this association increased as trees aged and grew.

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CRediT authorship contribution statement

Geoffrey H. Donovan: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Jeffrey P. Prestemon:** Methodology, Formal analysis, Writing – review & editing. **Demetrios Gatziolis:** Formal analysis, Writing – review & editing. **Yvonne L. Michael:** Conceptualization, Writing – review & editing. **Abigail R. Kaminski:** Formal analysis. **Payam Dadvand:** Writing – review & editing.

Declaration of Competing Interest

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

Data availability

The data that has been used is confidential.

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