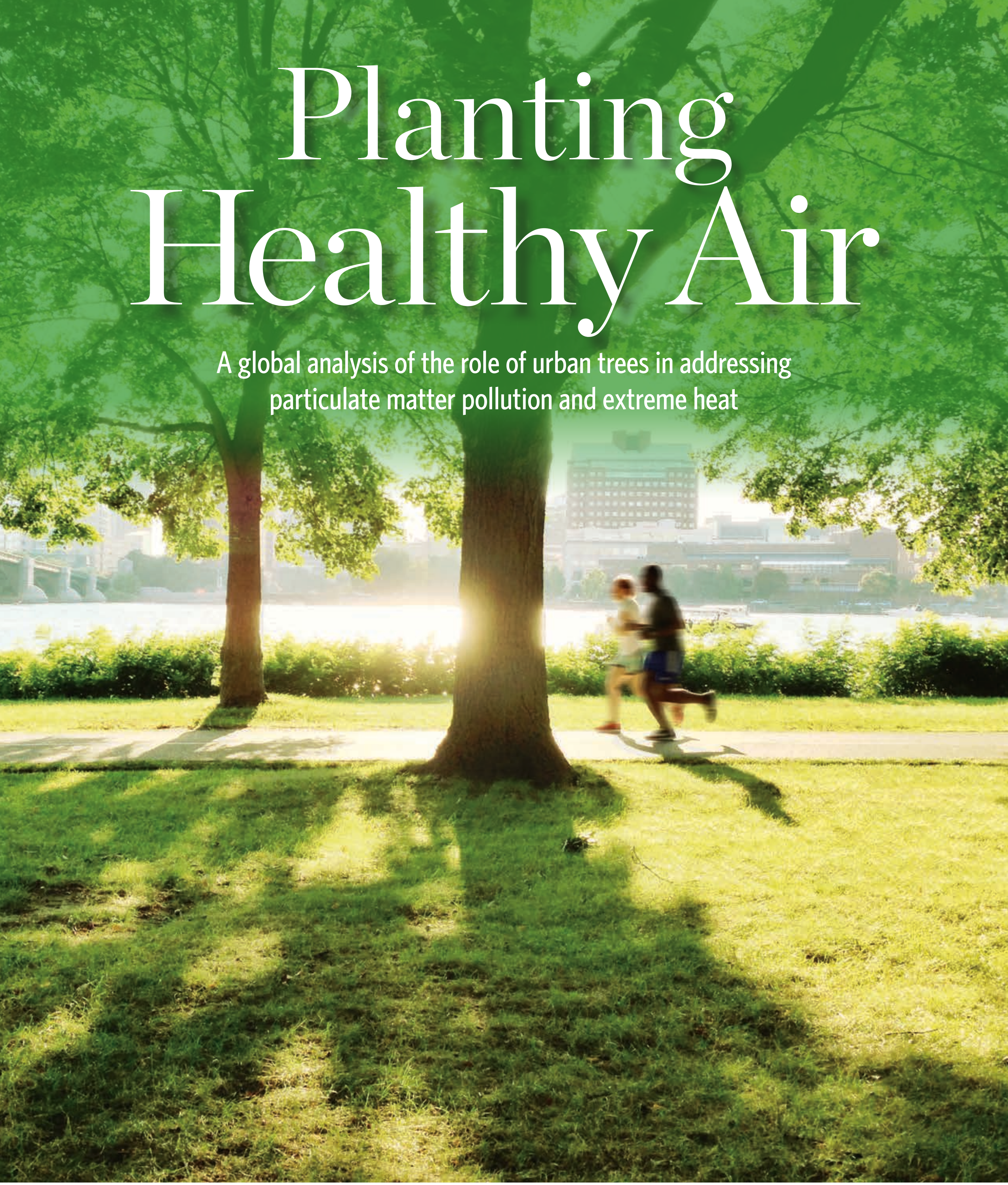
Planting Healthy Air

A global analysis of the role of urban trees in addressing particulate matter pollution and extreme heat



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By 2050,

the vast majority of humanity will live in cities, towns, and other urban areas.

Photo © Kevin Anold

Planting Healthy Air

The 21st century will be the urban century, as more than 2 billion additional people arrive in cities globally. This rapid urbanization is unprecedented in human history, and by 2050, the vast majority of humanity will live in cities, towns, and other urban areas.[1] Yet at this moment of the "triumph of the city,"[2] the world's urban areas are also facing many significant challenges, from providing jobs and utilities to a burgeoning citizenry, to protecting their residents from crime and violence, to safeguarding urban environmental assets. Among the most pressing of global urban environmental challenges is air quality. In most cities, the most damaging air pollutant is particulate matter, which is emitted from a variety of sources, especially the burning of agricultural residues, fuelwood, and fossil fuels.[3] Fine particulate matter (less than 2.5 micrograms, µg, in diameter, also known as $PM_{2.5}$) can be deeply inhaled into the lungs and is estimated to cause 3.2 million deaths per year (around 4 percent of the global burden of disease) (Figure E1), primarily from cerebrovascular disease (e.g., stroke) and ischemic heart disease (e.g., heart attack).[3, 4] $PM_{2.5}$ exposure also contributes to chronic and acute respiratory diseases, including asthma. And the problem has the potential to get worse: One study forecast that by 2050, fine particulate matter could kill 6.2 million people per year.[4] Cities and national governments are well aware of the threat $PM_{2.5}$ poses, and they are urgently looking for ways to reduce it.

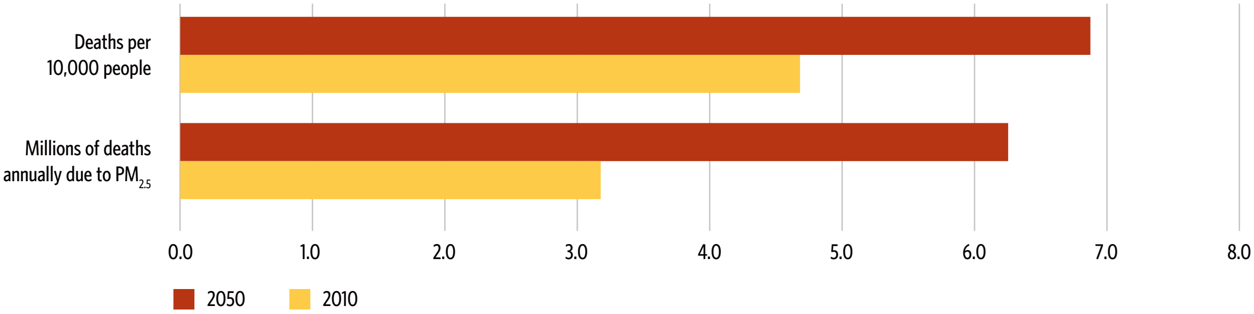


Figure E1. Forecasted global mortality from $PM_{2.5}$ in 2050 compared to 2010, expressed either as the total number of deaths, or as the number of deaths per 10,000 people. The number of people forecasted to be killed will almost double (i.e., increase by 100 percent). Some of that increase is due simply to population growth. The number of deaths per 10,000 people, however, is still expected to go up by roughly 50 percent, primarily due to an increase in $PM_{2.5}$ concentrations in cities in the developing world. Data taken from Lelieveld et al.[4]


Photo © Karine Aigner

Another pressing problem cities face is that the air is simply so hot in summer that human health is impacted. Already, heat waves are the weather-related disaster that causes the most mortality globally (Figure E2), killing an estimated 12,000 people on average annually[5] and making life unpleasant for millions. Climate change is only going to make the threat of urban heat waves more severe, as the increase in greenhouse gases traps more of the sun's energy, increasing the frequency and severity of heat waves.[6] One World Health Organization report forecasts that by 2050, deaths from heat waves could reach 260,000 annually,[7] unless cities adapt to the threat. Just as smart cities are trying to reduce their concentration of $PM_{2.5}$, thousands of cities are looking for ways to better manage—and adapt to—excess heat.

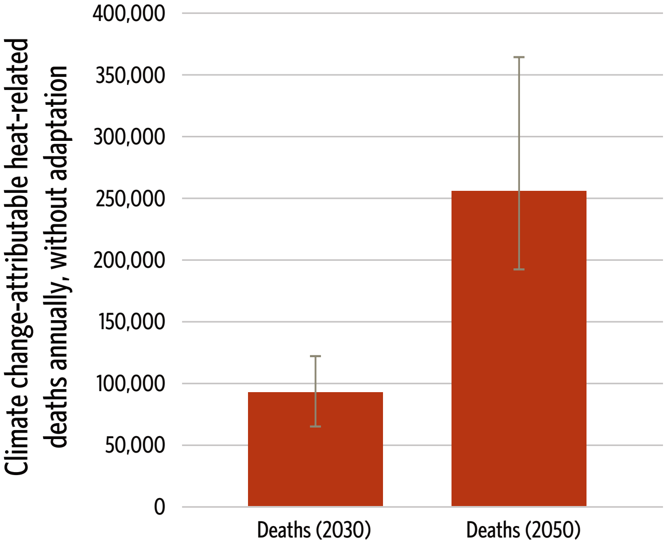


Figure E2. Forecast of climate change's impact on deaths due to excess heat, expressed as annual mortality numbers in 2030 and 2050. The WHO study looked at a range of climate scenarios, which cause a range of mortality (shown with the error bars). Data taken from WHO (2014).

Can nature help address these twin problems of air that is too dirty or too hot? Trees and other vegetation, whether planted along a city street or growing in a park or residential yard, provide many benefits to people, such as aesthetic beauty, enhancement of property values, erosion prevention, stormwater management, and noise reduction. Trees also sequester carbon, helping mitigate climate change. Parks also provide space for urbanites to recreate, which brings real physical and mental health benefits. It looks like trees may play an important role in making our air healthier, too. Dozens of studies now show that tree leaves filter out particulate matter from the atmosphere, along with many other air pollutants. Similarly, many scientific studies show that the shade trees cast, along with their transpiration of water during photosynthesis, can help reduce air temperatures while also reducing electricity use for residential cooling. But questions remain for urban leaders and public health officials:

- What fraction of the air-quality problem (particulate matter and excess heat) can trees solve?
- Which cities and which neighborhoods can be helped most?
- How much investment is needed, in terms of trees planted or dollars spent?
- Where are trees a cost-effective investment, relative to other strategies that can reduce PM or ambient air temperature?

Trees are already providing large benefits

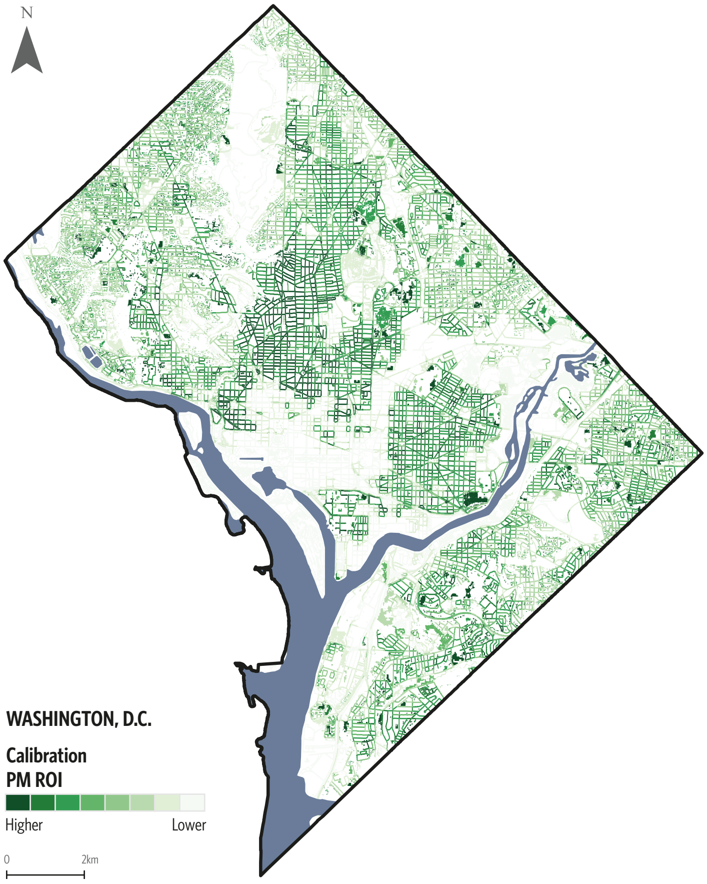
The Nature Conservancy conducted—in coordination with C40—the first global study of cities to answer these questions. We collected geospatial information on forest and land cover, $PM_{2.5}$ pollutant concentration, and population density for 245 cities, and then used established relationships in the literature to estimate the scope of current and future street trees to make urban air healthier. We established three scenarios (High, Medium, and Low) that describe the range of reduction in PM concentration and temperature that trees have been shown to provide. We focused our analysis on street trees, since our review of the scientific literature indicated that proximity between trees and people was needed to deliver meaningful reductions in PM or temperature. The 245 cities we studied currently house around 910 million people, or about a quarter of the world's urban population.

The current stock of street trees in our studied cities is already delivering real benefits. We estimate that trees are currently providing on average 1.3 million (Low scenario to High scenario range: 0.0 to 6.1) people at least a 10 $\mu g/m^3$ reduction in $PM_{2.5}$, 10.2 million (1.0 to 15.4) people at least a 5 $\mu g/m^3$ reduction, and 52.1 million (23.8 to 63.1) people at least a 1 $\mu g/m^3$ reduction. Similarly, trees are already providing 68.3 million people with a roughly 0.5 to 2.0° C (0.9 to 3.6° F) reduction in summer maximum air temperatures. As discussed in detail in the report, this magnitude of impact on PM and temperature has real health benefits for those affected.

These numbers are just for the current stock of street trees. As we show in the report, many cities are struggling to maintain their current stock of street trees, and our results emphasize the importance of investments to maintain this stock. However, in many cities there also exist substantial additional opportunities for adding tree cover to further mitigate air pollution and summer heat. In this study, we assessed the impact of such large-scale but feasible tree cover increases, measuring their return on investment (ROI) in terms of $PM_{2.5}$ reduction or temperature mitigation delivered to people per dollar spent.

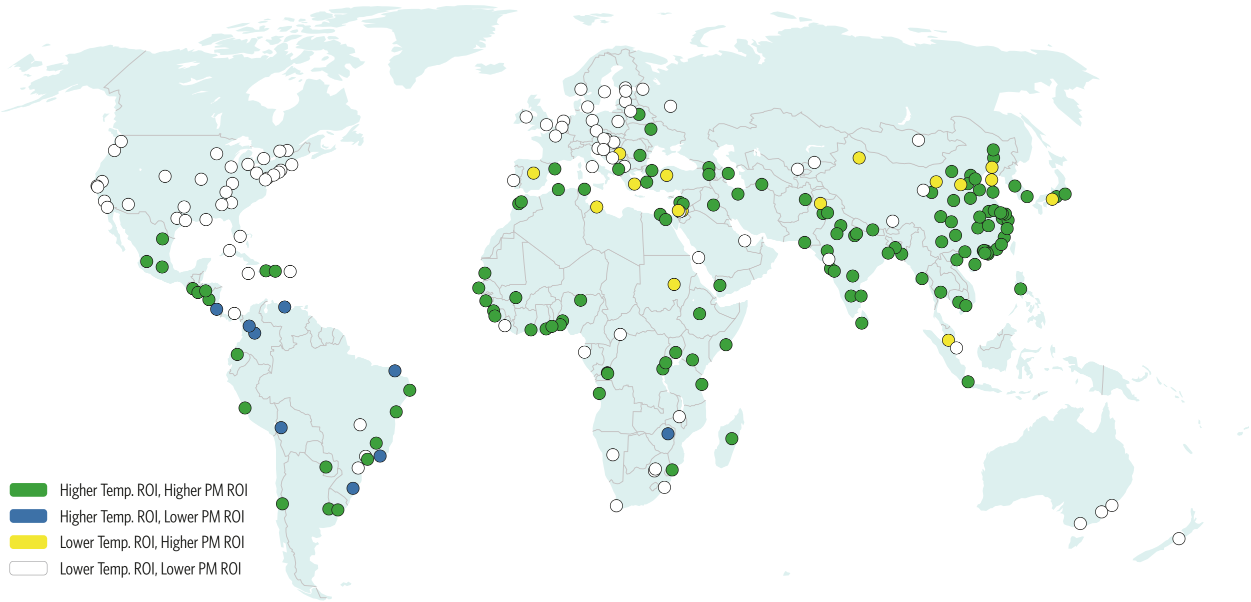
The importance of targeting

Our literature review showed that trees provide meaningful but locally concentrated reductions in PM and temperature, with the majority of mitigation generally within within 300 meters of plantings. Targeting the neighborhoods with the highest mitigation impacts becomes crucial (Map E1). Our results show substantial variation within cities, with the best neighborhoods for street tree planting often having 100-fold greater return on investment (ROI) in tree planting compared to the least suitable neighborhoods. Generally, those neighborhoods are characterized by higher population density and thus more people who will benefit from cleaner air, and by higher concentrations of $PM_{2.5}$ that can be removed by trees. We discuss guidelines for plantings in the report that can be used to select species with high PM removal capacity, as well as appropriate spacing among plantings, since it is important to avoid the trapping of airflow from particulate sources (e.g., highways) in areas where people are present. Population density and PM concentrations also drive variation among cities in ROI (Map E2). An additional factor that varies among cities is the cost of tree planting; all else being equal, cities with lower planting and maintenance costs have higher ROI. Globally, tree planting and maintenance costs tend to be lower in less developed countries. However, within countries, there is substantial variation among cities, driven by differences in availability of planting stock, labor costs, and the scale of a city's urban forestry program.



Map E. Neighborhood-level patterns in the return on investment (ROI) of tree planting to reduce particulate matter for one city, Washington, DC. Streets that are darker green have higher return on investment.

There are similar patterns in ROI of tree planting for air temperature mitigation, with ROI varying among neighborhoods 100-fold. The ideal high-ROI neighborhood would have high population density (or a concentration of sensitive populations) leading to a larger number of people benefiting from heat reduction by trees. We discuss planting guidelines for air temperature mitigation as well, noting where guidelines that maximize temperature mitigation diverge from guidelines that would maximize PM removal. Population density and planting costs drive large variance in ROI of temperature mitigation among cities (Map E2). Note, however that arid cities may face a trade-off when planting trees: While more trees will reduce maximum temperatures (and PM concentrations), they also require water, which may be scarce, for irrigation at least during part of the year.



Map E2. **Return on investment of tree planting to reduce ambient temperatures** for global cities.


Photo © Devan King.

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Nature is a cost-effective solution

Our research also shows that urban street tree planting and canopy enhancement can be a cost-effective way to make the air healthier. For particulate matter the cost of reduction, in $/ton, varies significantly across neighborhoods, and in some neighborhoods is lower than published emission-control costs for other available strategies (Figure E3). However, the median cost of tree planting for PM mitigation is higher than that of five out of six broad categories of strategies we considered, suggesting that in many cases other conventional PM reduction strategies may be less costly. The cost of reducing temperatures (in $/° C from implementing the practice over a 100-square-meter area area) also varies significantly across neighborhoods, and in some places is lower than for any available conventional strategy. The median cost of tree planting is less than every other strategy considered except for cool-roof technologies. Of course, in cases where both PM concentrations and high temperatures are a concern, the comparative attractiveness of tree cover additions would be much higher still, as none of the conventional "grey" alternatives address both heat and PM problems. Moreover, the other co-benefits that trees provide (carbon sequestration, aesthetic beauty, stormwater mitigation, etc.) further increase the comparative attractiveness of tree cover as a solution.

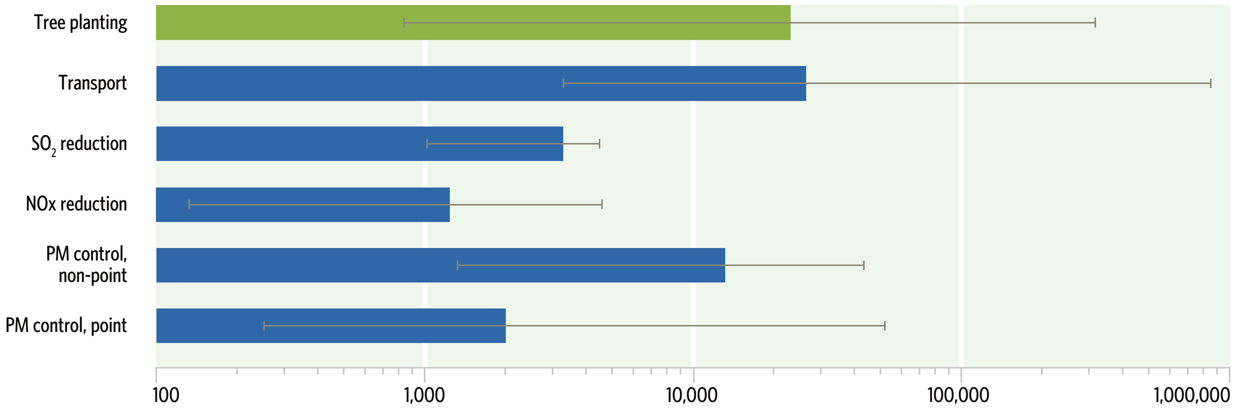
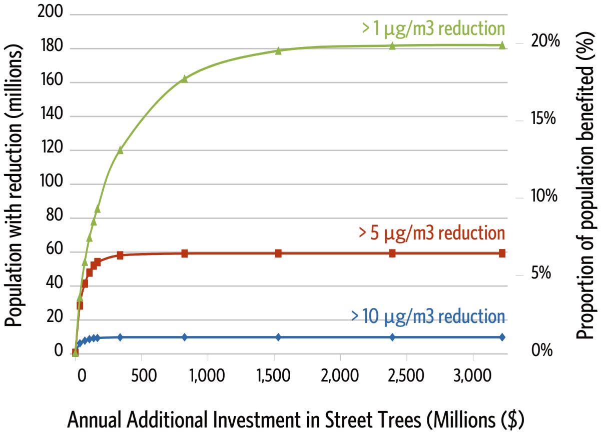


Figure E3. Cost-effectiveness of street tree planting to reduce particulate matter, compared with common categories of conventional mitigation strategies. The green bar shows the median cost-effectiveness of street tree planting across sites, while its error bars show the minimum and maximum cost-effectiveness. All values for cost-effectiveness are standardized to US2015$/ton. Note that while the median cost per ton PM removed is higher for street trees than the median cost of many conventional strategies, there is significant variance, and on many sites tree planting is cost-competitive relative to the other grey infrastructure strategies. Moreover, this comparison is biased in favor of conventional strategies because their cost-effectiveness is expressed in terms of $/ton emissions avoided at the emissions source (not all of which translates into local concentration reductions for people), while that of trees represents the actual cost-effectiveness in producing local reductions for people.

Not only can street tree planting in some neighborhoods be a cost-effective way to make air healthier, it can also deliver these benefits to a significant fraction of urban residents. The global investment curve for trees to reduce $PM_{2.5}$ pollution is shown in Figure E4. For instance, we estimate, under our Medium impact scenario, that an annual $100 million additional global investment in trees (including planting and maintenance costs) would give 8 million additional people a large reduction of $PM_{2.5}$ (> 10 µg/m^3), 47 million people a moderate reduction (> 5 µg/m^3), and 68 million people a modest reduction (> 1 µg/m^3). The shape of the investment curve for temperature looks similar (Figure E5). An annual investment of $100 million would give an additional 77 million people a 1° C (1.8° F) reduction in maximum temperatures on hot days (Medium impact scenario).



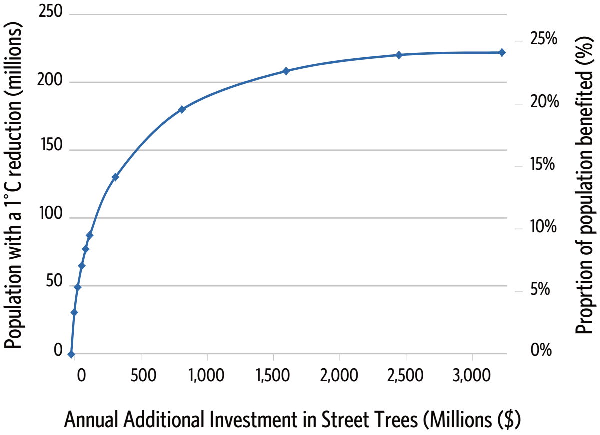


Figure E4 (left). The global potential for street trees to benefit urban dwellers with reduced PM concentrations, given different annual investments in tree planting and maintenance. Results shown are for our Medium scenario of the effectiveness of trees in removing PM. Note that the curves for 5 and 10 µg/m^3 flatten out at high investment levels because there are relatively few cities (principally the most polluted) where street tree planting can remove more than this amount of pollution. Once investment in street tree planting has fully occurred in these cities, additional investment in tree planting won't increase the number of people receiving a reduction of more than 5 µg/m^3, but will continue to increase the number of people receiving more modest reductions of 1 µg/m^3.

Figure E5 (right). The global potential for street trees to benefit urban dwellers with reduced temperatures, given different annual investments in tree planting and maintenance. Results shown are for the Medium scenario. Under the High scenario an equivalent number of people would see a 2˚C reduction, whereas under the Low scenario the same number of people would see a 0.5˚C reduction.

These magnitudes of reductions in $PM_{2.5}$ concentrations and temperature achievable with tree cover can provide modest but significant reductions in disease. Based on the well-established relationship between outdoor $PM_{2.5}$ concentration and mortality, we estimate that the maximum possible tree planting in our cities (cost = $3.2 billion annually) would reduce PM-related mortality by 2.7 percent to 8.7 percent, saving between 11,000 and 36,000 lives annually in our study cities. In this executive summary, we focus only on mortality numbers, but there are, of course, a range of health impacts, from missed days at school or work to hospitalizations to premature death. Research indicates that for every death from $PM_{2.5}$ there are many people hospitalized or otherwise affected by PM, so we expect that, similarly, the number of people who would benefit in some way from the maximum possible tree planting would be many times larger than the avoided mortality figure.

The effect of high temperature on mortality is also well documented in the literature. Based on studies that functionally relate mortality to high temperature, we estimate that the maximum possible tree planting in our cities would reduce high temperature-related mortality by 2.4 percent to 5.6 percent, saving between 200 and 700 lives annually in our study cities. Note that this figure is for the current climate, and with climate change potential increasing mortality from heat more than 20-fold, it seems likely this figure of lives saved by street trees will be substantially larger in the future.

Additionally, tree planting could reduce electricity use and increase carbon sequestration. We estimate that our maximum possible street tree-planting scenario would reduce residential electrical use in our 245 cities by 0.9 percent to 4.8 percent annually (9.8 billion to 48 billion KWhr). Under the maximum street tree-planting scenario, net carbon sequestration would increase by 2.7 million to 13 million tons CO_2. Combined with estimates of the avoided CO_2 emissions due to electricity use reduction, we estimate the total impact of our maximum street tree-planting scenario as an annual reduction of 7.0 million to 35 million tons CO_2. Note that these climate mitigation benefits are provided in addition to the benefits to human health from PM reduction and temperature mitigation.

Nature will matter even more in the future

Finally, our analysis of trends over time suggests that the ecosystem services supplied by trees will be even more crucial in the future. There may be a 50 percent increase in the rate of mortality caused by $PM_{2.5}$ by 2050, most of it in urban areas,[4] and summer maximum temperatures in our sample of cities are forecast to increase by 2-5˚C (4-9° F) over the same time period. While these twin threats post a challenge to the health of those in cities, all else being equal, they will also increase the importance of the trees that are already there. There will also be a dramatic increase in urban population, which increases the number of people who might benefit from nature's services. Finally, all this urban development, or simply societal underinvestment in replacing trees lost, may reduce the amount of urban greening. For instance, we found that 26 percent of cities had a decline in forest cover over the period between 2000 and 2010, whereas only 16 percent of cities had an increase in forest cover over the time period.

Conclusions

We are at the beginning of the urban century. One of the preeminent tasks of cities will be making themselves vibrant, healthy, attractive places to live. This report has focused on just one small part of this task: the quest to make urban air healthier. Cities continue to strive to reduce concentrations of particulate matter and other atmospheric pollutants. And they are beginning to plan for the increased frequency and intensity of heat waves that climate change will likely bring. Succeeding against these twin challenges—air pollution and excess heat—will require an array of approaches. In this report, The Nature Conservancy – in coordination with C40 Cities Climate Leadership Group – has tried to understand whether nature can play a role in helping to solve these twin challenges.

The answer appears to be a qualified "yes." Street trees can be a part of a cost-effective portfolio of interventions aimed at controlling particulate matter pollution and mitigating high temperatures in cities. While trees cannot and should not replace other strategies to make air healthier, trees can be used in conjunction with these other strategies to help clean and cool the air. Moreover, trees provide a multitude of other benefits beyond healthier air. In the right spot, trees can both help make our air healthier and our cities more verdant and livable.


Photo © Richard Howard.

Chapter 1

Photo © Hanohiki

The Urban Air Crisis

Cities globally face many environmental challenges, from protecting their drinking water supply to managing their wastewater to building enough parks and street trees to satisfy the needs of their residents. Some of these challenges are idiosyncratic, and some are universal challenges facing all cities. One of the biggest challenges facing cities globally is keeping their air healthy. This report focuses on two crucial issues: air pollution and extreme high ambient air temperatures, both of which impose significant costs on cities. In this first section, we outline the scope of these two crucial issues cities are trying to manage to maintain healthy air.

Air pollution from particulate matter

Globally, particulate matter is the ambient air pollutant with the largest health burden. Particulate matter is responsible for an estimated 3.2 million premature deaths annually, in both rural and urban areas. This mortality amounts to over 5 percent of all global premature deaths.[1] Particulate matter also causes a range of other non-fatal health problems that affect tens of millions of people annually, including coughing, asthma, bronchitis, irregular heartbeat, and non-fatal heart attacks. Municipal and national governments worldwide struggle to reduce particulate matter concentrations (Photo 1).


Photo: David Holt, Creative Commons license, Flickr

Photo 1. A view over London on a bad air pollution day, with the skyline almost completely obscured.

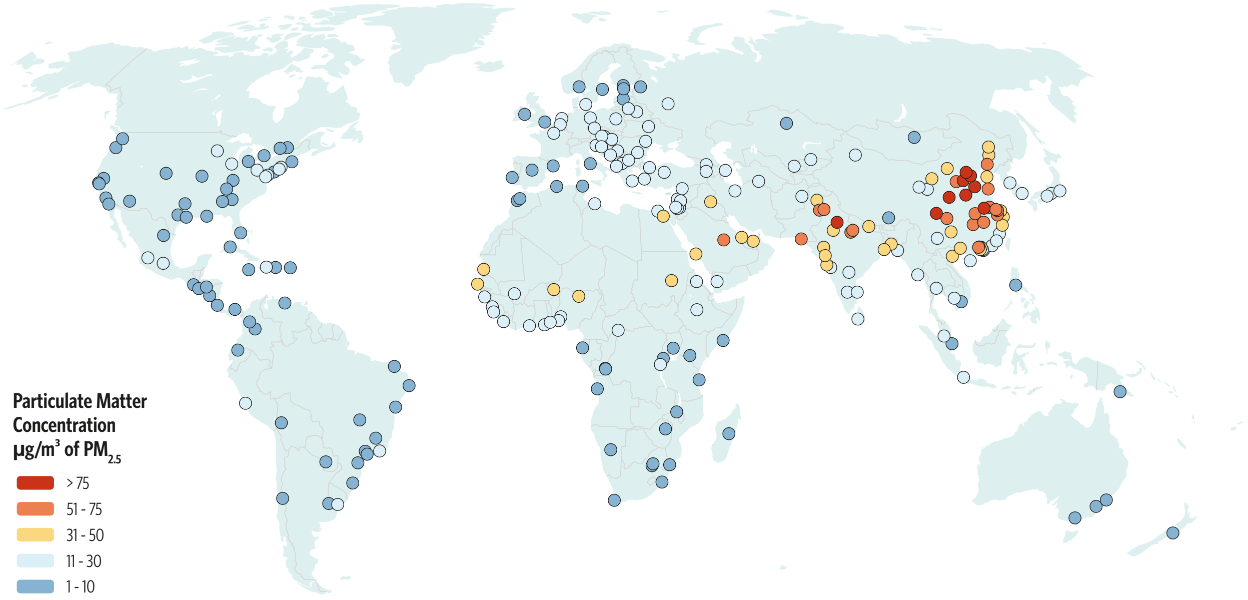
Photo 2. Photo: United Nations, Photo: Flickr.

Particulate matter—the basics

Particulate matter (PM) is defined as any molecule or particle that can be transported in the atmosphere. PM is classified by the size of the particle, and size matters because it determines how easily and deeply humans inhale the particle into their lungs. Standard measurements are PM_{10} (smaller than 10µm) and $PM_{2.5}$ (smaller than 2.5 µm).[2] Smaller particles ($PM_{2.5}$) are of higher concern from a human health perspective than the coarse particle fraction ($PM_{10\text{-}2.5}$), but both have negative health impacts.

PM comes from a variety of sources (Photo 2). Globally, residential-level burning of biomass or fossil fuels for heating or cooking is a major source of PM. So is the burning of fossil fuels at larger stationary sources, like factories and power plants. The transportation sector is also a major source, as is the agricultural sector, which can release large quantities of PM when agricultural residues are burned. While global estimates are available for the average contribution from each source, there is considerable variability among cities regarding where their PM comes from. There are also often different sources for PM depending on particle size. For the larger PM_{10}, dust from roads (a result of road, tire and brake wear) and construction operations are major sources of emissions, as is sea salt for coastal areas. For the smaller $PM_{2.5}$, direct (primary) emissions from the burning of biomass or fossil fuels are the major source. Secondary emissions, which occur when a molecule is transformed through physical or chemical processes, are also important for $PM_{2.5}$. For instance, nitrogen oxides (NOx) and sulfur oxides (SOx) can react to form particulate matter.[2]

This complex overlay of sources leads to radically different concentrations in cities globally (Map 1). The highest concentrations globally of $PM_{2.5}$ are found in China and northern India. The Middle East and North Africa also have high concentrations, with a large fraction of their PM coming from desert dust. Urbanized Europe and the Eastern United States have more moderate levels of PM, while some of the lowest average concentrations are found in Australia, southern Africa, and parts of South America. While struggling against PM is a common theme for almost all cities, the battle is significantly harder in certain parts of the world that also contain the majority of humanity's urban populations.



Map 1. Particulate matter concentration (PM$_{2.5}$ in µg/m^3) for global cities in this study. To smooth out yearly variability, we display the average concentration over the period from 2010 to 2014.

Particulate matter and health effects

As discussed above, particulate matter has multiple negative health consequences (Figure 1). Around two-thirds of this health impact appears to be related to the way PM increases the incidence of cardiovascular and pulmonary disease. Particularly important are cerebrovascular diseases (e.g., strokes) and ischaemic heart disease (e.g., heart attacks). A recent review of the literature concluded, "The data demonstrating PM's effect on the cardiovascular system are strong. Populations subjected to long-term exposure to PM have a significantly higher cardiovascular incident and mortality rate. Short-term acute exposures subtly increase the rate of cardiovascular events within days of a pollution spike."[3]

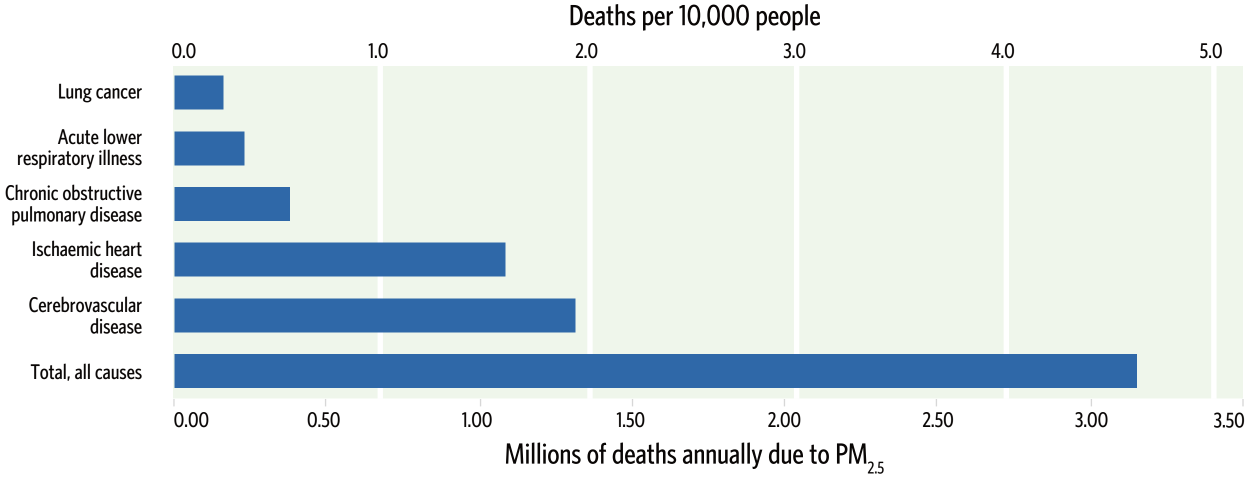


Figure 1. Estimated global mortality from PM$_{2.5}$, expressed either as the total number of deaths (bottom axis, in millions), or as the number of deaths per 10,000 people (top axis). All figures are for the year 2010. Data taken from Lelieveld et al. (2015).

Current World Health Organization (WHO) guidelines are less than 20 micrograms per cubic meter (µg/m^3) for PM_{10}, and less than 10 µg/m^3 for $PM_{2.5}$.[4] However, research suggests there is no safe level of exposure to PM, and that any reduction in PM levels has health benefits. For instance, Daniels et al.[5] estimated PM-mortality dose response curves and found a linear relationship between PM_{10} concentrations and relative risk of death, overall and specifically for cardiovascular causes. What this means is that, whatever the current concentration of ambient PM in a city, reduction in PM levels will lead to health improvements.

A large number of studies in the last decade have looked at how changes in PM have affected health. For instance, Pope et al.[6] looked at 1.2 million patients and found that each 10 µg/m^3 increase in $PM_{2.5}$ was associated with a 9 percent increase in cardiopulmonary mortality. And this association is not just true for a moment in time, but true over time. One study (the Harvard Six City Study) followed U.S. patients for more than 20 years. Their exposure to PM concentrations changed over time, as they moved between cities with varying concentrations or as environmental regulations in the United States decreased PM concentrations. Each 10 µg/m^3 increase in $PM_{2.5}$ exposure resulted in a 14 percent increase in all-cause mortality.[7] Another famous example of reductions in PM having measurable benefits to human health comes from Dublin, Ireland[8] (Figure 2), where a ban on sales of coals in 1990 led to significant decreases in black smoke and immediate impact on cardiovascular health.

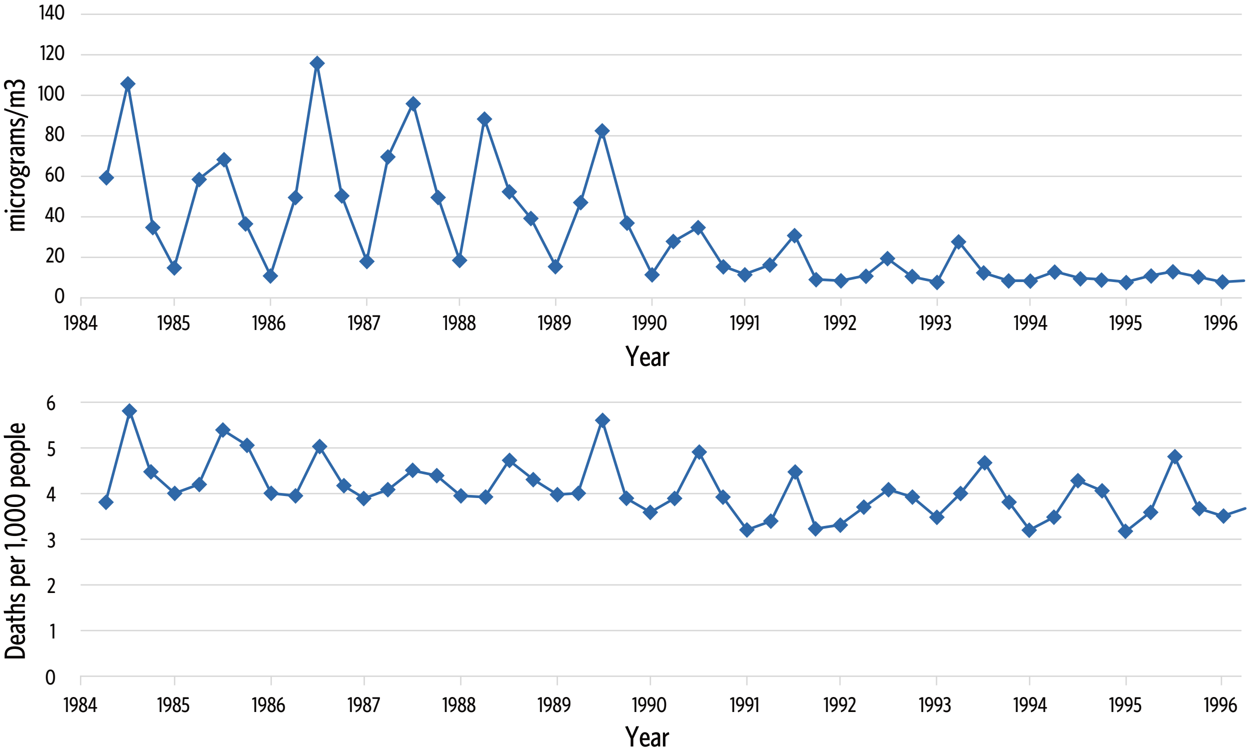


Figure 2. PM health connection data from Dublin study. One of the most famous case studies of how reduction in particulate matter pollution can improve health comes from Dublin, Ireland, which banned sales of coals in the city in 1990. In the three years following the ban (upper figure), black smoke concentrations decreased by 35.6 µg/m^3, and cardiovascular mortality (lower figure) decreased by 10.3 percent. Figures adapted from Clancy et al. (2002).[8]

In some ways, it is surprising that there is such a strong empirical relationship between ambient outdoor air quality and health, since many people in cities spend the majority of their time inside. Indeed, indoor air pollution from, for instance, the burning of fossil fuels and biomass for cooking, is also a major public health problem.[1] Indoor and outdoor air quality are also related, in that the same activity (e.g., burning biomass or fossil fuels for cooking or heating) may contribute to higher PM concentrations in both of them. Moreover, a surprisingly large fraction of outdoor PM can infiltrate into homes, so in some cases outdoor PM is a major contributor to indoor concentrations.[9]

Regardless, there is a strong and robust scientific literature that shows that reductions in ambient outdoor concentrations of PM will reduce people's exposure to these pollutants during the hours they spend outdoors, and will lead to quantifiable reductions in mortality and morbidity.

Photo 3. There are a variety of ways cities try to reduce particulate matter pollution. Many cities try to convert buses and other vehicles from diesel, which heavily pollutes particulate matter, to compressed natural gas (CNG). This photo shows CNG buses in Stockholm, Sweden.

Commonly used strategies to reduce PM

There are a large number of strategies that can be used to reduce PM emissions (Photo 3), and which strategies are appropriate and cost-effective depends on the city and its emission profile. In this brief survey of commonly used strategies to reduce PM, we lump these strategies into five broad categories (Figure 3).

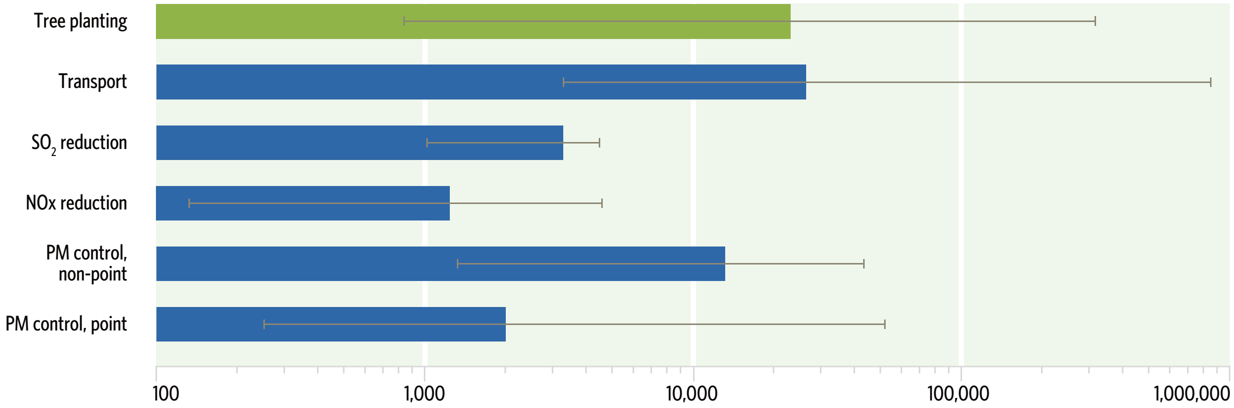


Figure 3. Cost-effectiveness of grey infrastructure strategies to reduce particulate matter. Each category contains multiple individual technologies cited in the literature, in the United States, Chile, Mexico, Taiwan, and the UK. The bar shows median cost-effectiveness, while the error bars show the minimum and maximum cost-effectiveness observed in the category. All values for cost-effectiveness are standardized to US2015$/ton.

- **Transportation sector reductions—**A variety of technological changes and upgrades to the vehicle fleet can significantly reduce the amount of particulate matter. A focus often is on older vehicles, particularly those with diesel engines that can contribute disproportionately to PM emissions. Switching the fuel these engines run on can significantly reduce PM emissions. For instance, Delhi has switched most of its taxi and bus fleet over to running on compressed natural gas, which has lowered emission of several problematic air pollutants for the city, including PM. The return on investment (ROI) of transport sector strategies, as measured in $/ton of PM varies widely, depending on the cost of implementing the strategy and how much PM reduction is achieved.

- **Sulfur Dioxide (SO^2) reductions—**Since sulfur dioxide can react to form PM, strategies that reduce sulfur dioxide can reduce PM concentrations. Reducing sulfur dioxide also directly improves human health, since sulfur dioxide causes numerous respiratory and cardiovascular diseases. Sulfur dioxide forms primarily from the burning of fossil fuels such as coal, oil, and diesel fuel. Controlling sulfur dioxide emissions therefore often involves either making the burning less polluting by technological upgrades, or finding a way to switch to a cleaner-burning fuel. Again, the costs ($/ton) varies widely.

- **Nitrogen oxide (NO_X) reductions—**Nitrogen oxide can also react to form PM, so strategies that reduce nitrogen oxide can reduce PM concentration. Reducing nitrogen oxide concentrations also helps avoid the respiratory issues caused by exposure to nitrogen oxide. Nitrogen oxide comes from a variety of sources, including agricultural soil management and the burning of fossil fuels; therefore, there are a variety of strategies governments can pursue to reduce emissions.

- **PM control, non-point—**Often, particulate matter makes its way into the atmosphere not from a concentrated high-emission “point” source (e.g., a smokestack), but from large numbers of widely distributed sources with individually low emissions. For instance, unpaved roads, construction sites, cooking stoves, and bare agricultural fields can all be non-point sources of PM. There are control strategies for each of these types of sites. For instance, on agricultural land, using cover crops or following no-till practices can reduce PM emissions. Also included in this category are strategies to reduce emissions of particulate matter from individual household burning of fuels for heating or cooking. These dispersed emissions from fuel burning are a significant source of PM in many cities in the developing world, and so strategies to reduce them are key to controlling overall PM concentrations. For instance, many cities have historically made the decision to ban the individual burning of coal in order to ensure air quality is maintained.[10]

- **PM control, point—**In many cities, point sources of particulate matter can be significant, such as the emissions coming from factories or power plants. There are a variety of technologies that can reduce PM emissions. For instance, there are a variety of filters (e.g., bag or fabric filters, wet scrubbers) that can capture PM. There are also electrostatic precipitators (ESPs) that can capture PM that can be installed separately or with filter technologies. These point-source pollution controls can be expensive to install, but because they often remove significant quantities of PM, the cost in terms of $/ton is quite low.

The future of PM emissions

Someone once joked that predictions are hard, especially when they are about the future. But while the future is uncertain, it seems likely that cities will continue to struggle with controlling PM concentrations over the coming decades. More people in urban areas and greater per-capita consumption of energy may increase PM emissions. At the same time, governments are continuing to invest in strategies to control PM, often starting with those with low marginal costs ($/ton), and over time moving to control strategies that are more expensive. It is this increasing marginal cost of PM control over time that drives governments to begin to consider a variety of strategies that can collectively meet the need for PM reduction, including potentially nature-based solutions, the focus of this report.

One study[11] looked at current health impacts of particulate matter and tried to estimate future health impacts (Figure 4). Total deaths attributable to $PM_{2.5}$ are predicted to almost double by 2050, from roughly 3 million to 6 million deaths per year. However, a lot of this increase is due to there simply being a lot more people in cities by 2050, as the massive urbanization of the 21st century continues. The death rate, expressed as the number of deaths per 10,000 people, is forecast to increase more modestly, from around five deaths per 10,000 people to around seven deaths per 10,000, a 40 percent increase. It is important to remember that this is only one scenario of what might happen in the future. If the world’s cities were to invest more aggressively in PM control technologies, the death rate could be held at the same level or even decline.

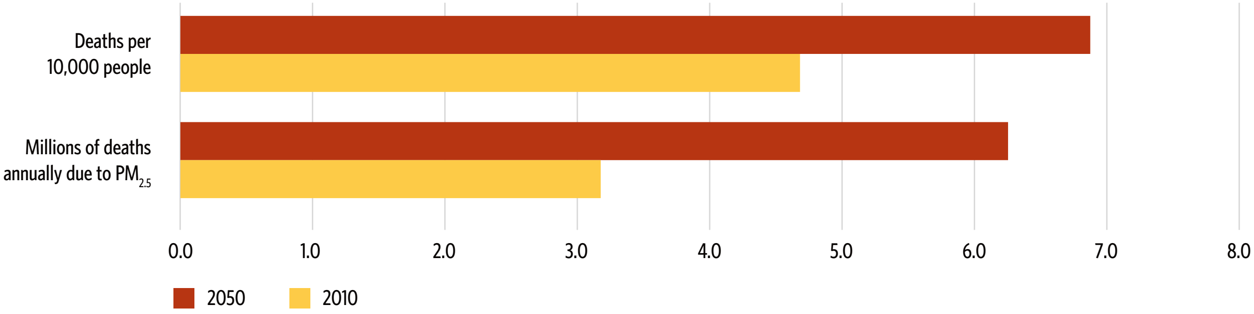


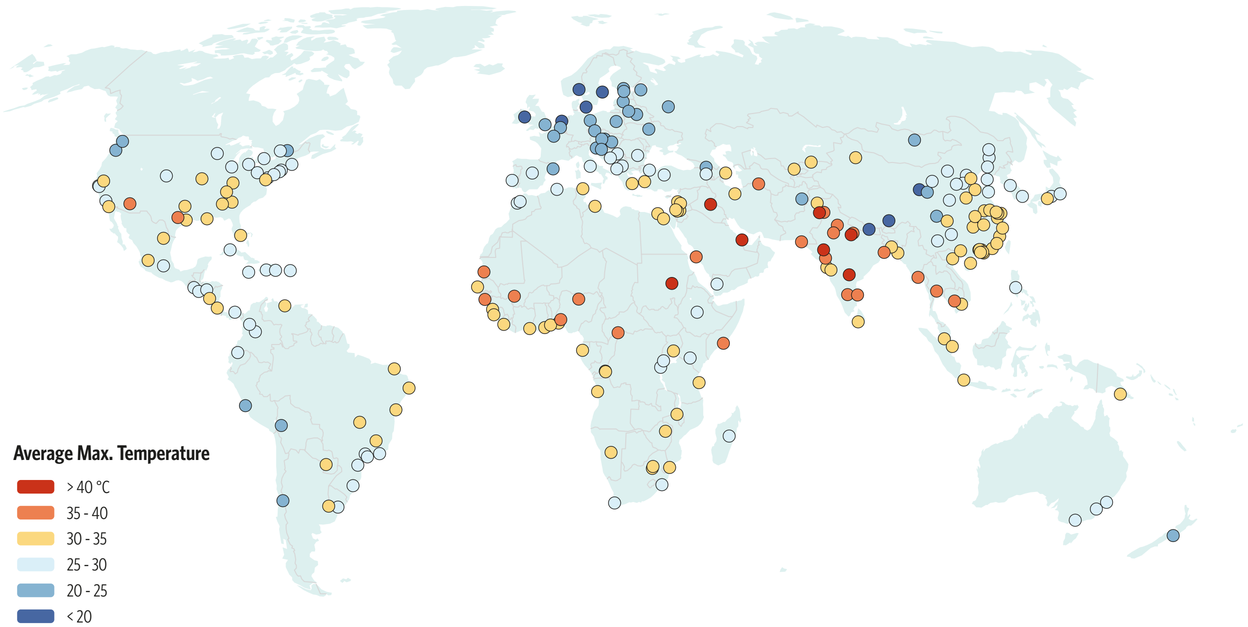
Figure 4. Forecasted global mortality from $PM_{2.5}$ in 2050 compared to 2010, expressed either as the total number of deaths, or as the number of deaths per 10,000 people. The number of people forecasted to be killed will almost double (i.e., increase by 100 percent). Some of that increase is due simply to population growth. The number of deaths per 10,000 people, however, is still expected to go up by roughly 50 percent, primarily due to an increase in $PM_{2.5}$ concentrations in cities in the developing world. Data taken from Lelieveld et al.[11]

Excess heat

Another major challenge that cities face is dealing with urban heat waves and other problems caused by air that is too hot. This section discusses that problem, as well as common solutions used to mitigate the effect of excess heat.

Ambient air temperatures—the basics

Air temperature is simply a result of how energetic and fast-moving gas molecules are on average. Humans are adapted to live in a specific range of temperatures, and extreme cold or hot temperatures cause a number of problematic effects for human health and society. The focus of this report is on hot temperatures, which occur when there is more heat energy in the atmosphere than is comfortable for humans. Average maximum summer air temperatures in cities globally vary greatly, from less than 23° C (73° F) for some far northern European cities to more than 36° C (97° F) for some sub-Saharan African and Middle Eastern cities (Map 2).



Map 2. Average annual maximum temperature (°C) for the period from 1960 to 1990. This period is often used as a reference period for "normal" temperatures before the impact of climate change.

Why is there such a large variation in temperature? The energy balance in the atmosphere[12] can be described as:

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A$$

The left hand side of the equation are inputs of energy into the air: Q* (the amount of energy from solar radiation) and Q_F (waste heat emitted from human activities, such as hot air from machines and cars). Generally, for most cities in the summer months, waste heat is a relatively small fraction of the input energy. The very hot cities globally are those with large inputs of energy from solar radiation.

The right hand side of the equation are places that energy can go. A fraction of the input energy can get stored somewhere, like in concrete or asphalt (ΔQ_S), and wind can carry some of the energy away from the city (ΔQ_A). The remaining energy has to go somewhere. It can increase sensible heat, Q_H, which increases air temperature. It can also increase "latent heat", Q_E, which is essentially the energy used up when water goes from its liquid to its vapor phase (e.g., evaporation).[13]

The term "latent heat" can be a bit confusing in the context of discussing the energy balance of the atmosphere. One example of how the latent heat of evaporation can reduce sensible heat: When you sweat on a hot day and the sweat evaporates, the conversion of liquid water to water vapor takes energy (latent heat) from the atmosphere and your skin surface (sensible heat). All else being equal, if a lot of the input energy from the sun (or waste heat) goes to latent heat, less of it will go to sensible heat.

Cities have large areas of impervious surfaces, and a large amount of energy (ΔQ_S) is stored and later released, relative to what would happen in the countryside. This release is lagged in time, taking hours for the energy to be fully released. This is sometimes referred to as the urban heat island (UHI), which is simply the increase in temperature in urban compared to rural areas. Urban centers can often be 2° C or higher in air temperature than surrounding rural areas. This report will focus on the general goal of reducing air temperatures to maintain public health and well-being, not specifically on reducing the UHI—but obviously the two are related.

Excess heat and health impacts

Exposure to high temperatures leads to a number of negative health effects. A set of diseases called heat injuries are directly attributable to acute, short-term exposure to heat. Most commonly, acute exposure to heat, combined with dehydration, can lead to heat cramps and fainting. Continued exposure can lead to heat exhaustion, which combines the above symptoms with headache, feelings of dizziness and confusion, pale skin, and profuse sweating. In even more serious acute exposure to extreme high temperatures, heat stroke occurs when internal body temperature rises to above 40° C (104° F). Untreated heat stroke can quickly lead to damage to the brain, heart, kidneys, and muscles, and in some cases coma or death. A relatively small number of deaths are directly caused by heat stroke.[14]

Epidemiologic studies, however, show a significant rise in overall mortality during periods of high temperature. Note that temperatures do not have to be extreme to cause an increase in overall mortality, but simply above average for the summer months for a city. Most of this increase in mortality occurs because high temperatures are risk factors for other diseases. High temperatures, for instance, increase the risk of heart attack and stroke, particularly in elderly populations. This epidemiological approach, estimating total mortality caused by high temperatures, shows that high temperatures are the weather-related disaster that causes the most mortality globally (Figure 5), killing on average 12,000 people annually.[14] Note that this estimate is from 2004, and the current global average mortality is likely higher: Climate change is dramatically increasing global temperatures, with eight of the 10 warmest years in the last century occurring after this 2004 study was published.[15]

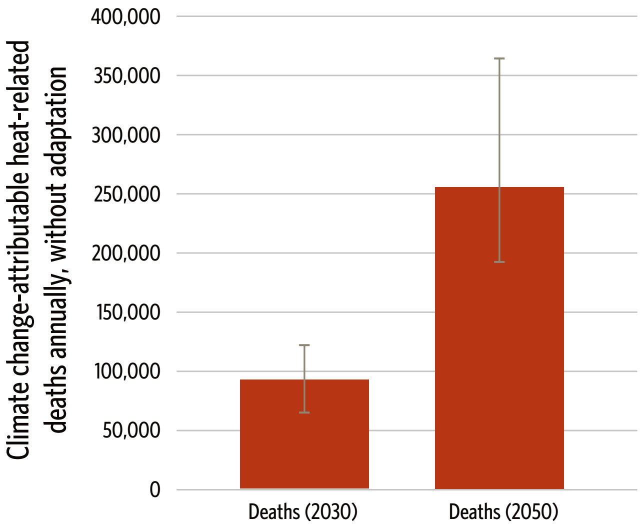


Figure 5. Forecast of climate change's impact on deaths due to excess heat, expressed as annual mortality numbers in 2030 and 2050. The WHO study looked at a range of climate scenarios, which cause a range of death (shown with the error bars). Data taken from WHO (2014).

Mortality from heat is highly episodic, and is concentrated in particular heat events. Table 1 lists a few major heat waves and their estimated health effects. One of the most well-studied heat waves occurred in Europe in 2003, when up to 70,000 may have been killed by a massive heat wave.[16] In early August, temperatures began to rise. In some parts of France, daily temperatures were 8° C (14° F) greater than usual.[17] A later analysis found that mortality rates in Paris were 142 percent higher in August than normal.[18] Microclimate, the temperature of particular neighborhoods, was a strong predictor of death rates.[19] Not surprisingly, warmer neighborhoods were more likely to be fatal: Each increase in temperature of 1° C raised the odds of death during this particular heat wave by 21 percent.

Location	Year	Health impacts
United States (eastern)	1901	9,500 killed
United States (Midwest)	1980	1,700 killed
Greece (Athens)	1987	More than 1,000 killed
United States (Chicago)	1995	739 killed
Europe	2003	70,000 killed
India (Andhra Pradesh and Telangana)	2015	More than 2,200 killed

Table 1. Selected major heat wave events that have been studied, as well as their health impacts. These were selected based on available studies in the scientific literature. In general, there has been more study of this issue in the United States and Europe, which partially explains the large number of heat waves listed in those geographies.

Other global studies have constructed curves that relate overall all-cause mortality to the excess temperature above some safe baseline, with each 1° C increase being associated with a 3.0 percent to 5.5 percent increase in all-cause mortality and a 1.1 percent to 2.6 percent increase in cardiovascular mortality specifically.[14] Another recent report by the World Health Organization[20] used the functional relationships from Honda et al.,[21] where, for instance, a 10° C increase above baseline causes a roughly 18 percent increase in all-cause mortality, and a 20° C increase above baseline increases all-cause mortality by roughly 50 percent. While the safe baselines used in the various studies differ, for context during the European heat wave of 2003, some cities were roughly 15 to 20° C above the safe baselines.

Commonly used strategies to reduce excess heat

From the perspective of a municipal official, there are only a few ways to decrease ambient (outdoor) air temperatures. The official can't reduce solar input or change overall wind patterns. Increasing building insulation can reduce the anthropogenic sources of heat, Q_F, but this is of relatively little importance during hot summer months. Most strategies to combat the urban heat island, therefore focus on reducing heat storage, ΔQ_S, by either increasing the reflectivity (albedo) of surfaces, which reflects more of the sun's energy back into space (Photo 4), or by shading surfaces that might otherwise store heat. Alternatively, some strategies increase evaporation or transpiration of water, which increases latent heat (Q_E) and therefore decreases sensible heat.

Photo: © iStock Lakeview_Images

Photo 4. Cool-roof technologies are one alternative strategy cities can use to reduce temperatures. Cool roof coatings can be simply a layer of white paint, as shown here. There are also a variety of shingles and other coverings that are more reflective than traditional building materials.

For simplicity, in this report we describe the cost-effectiveness of three broad categories *(Figure 6)*:

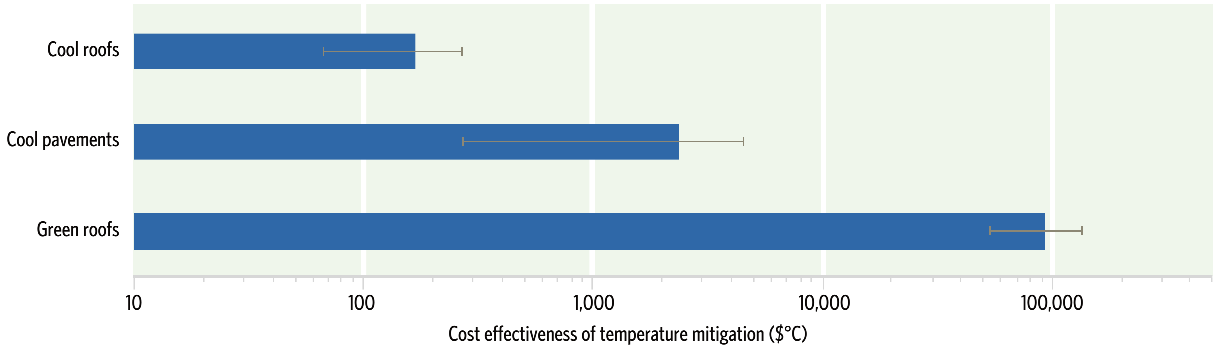


Figure 6. Cost-effectiveness of alternative strategies to reduce air temperature. Cost-effectiveness is expressed as the cost to build a 100100-square-meter installation, divided by the annual reduction in temperature. Data taken from the EPA's Reducing Urban Heat Islands: Compendium of Strategies, which discusses in more detail specific technologies within each of these broad categories. The reduction in air temperature is taken from a modeling study for New York City that quantified citywide reduction in temperature from widespread adoption of each strategy (Rosenzweig et al., 2006).

- Cool roofs—A cool roof is simply one covered with materials designed to increase the reflectivity of the roof and decrease heat storage. In some cases, this can be as simple as a highly reflective coat of paint. There are also reflective sheet coverings, as well as tiles and shingles that are more reflective than typical building materials. The EPA Compendium of Strategies to reduce air temperatures[22] has a good discussion of specific cool-roof technologies, and shows that they generally are only slightly more expensive to install than traditional materials and can deliver significant savings to building electricity use.

- Cool pavements—A similar strategy can be used to increase the reflectivity of pavements and decrease heat storage. The technologies available vary between asphalt (bitumen) concrete and cement concrete pavements. For asphalt concrete, the typically black asphalt serves as a binder and is mixed with aggregate particles to make the hard pavement. More highly reflective aggregate particles can be used, combined with lighter color or clear binders. Alternatively, there are cool coatings that can be put on top of the asphalt concrete. For cement pavement, the cement binder is already naturally fairly reflective, and is mixed with aggregate particles to make the hard pavement. Finally, permeable pavement that allows water to percolate through also will tend to increase evaporation of water from the surface, increasing latent heat storage and thus decreasing sensible heat.

- Green roofs—An alternative strategy for buildings is to plant vegetation on the roof. The presence of plants shades the roof, preventing heat storage. The plants will also transpire water, while some will also evaporate from the soil surface, increasing latent heat storage and thus decreasing sensible heat. Having

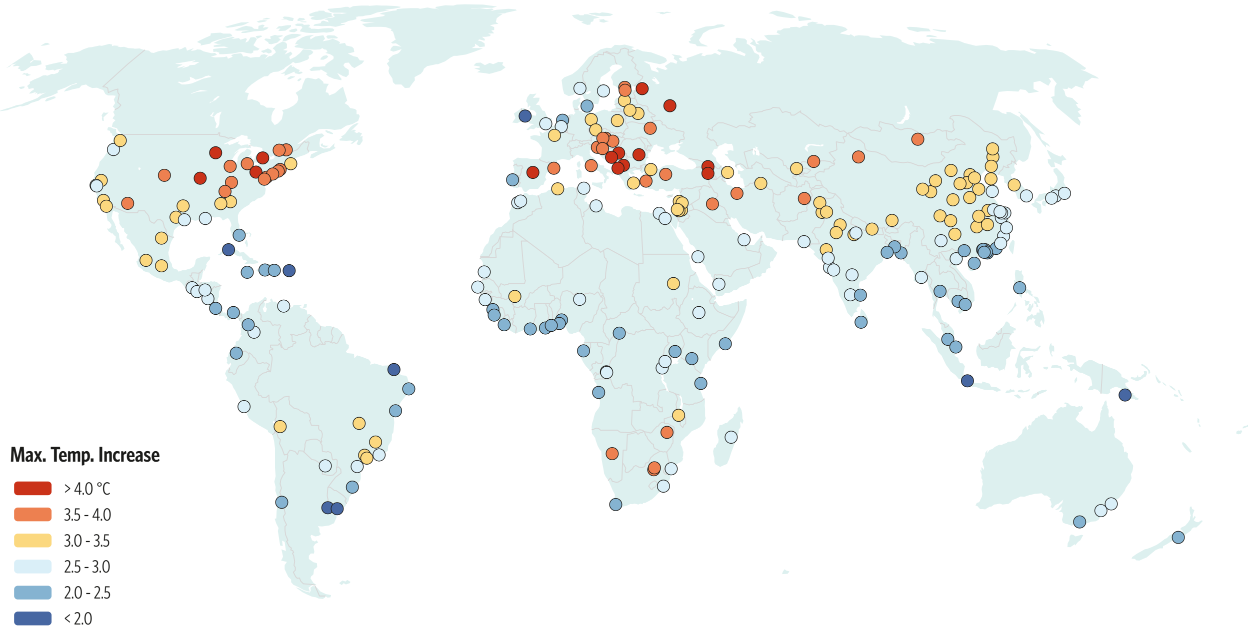

Photo © iStock, ilvuk8691

an attractive green roof provides many benefits beyond heat mitigation, including aesthetic beauty for the building's residents and increasing the property value. The main challenge for green roofs is that they are relatively expensive to install on roofs that weren't designed to support soil and plants, and the cost of retrofitting a roof to make it green can be significant.

The future of urban heat

Urban heat waves will only pose a greater challenge for cities in coming decades. First, there will be many more people in urban areas, with more than 2 billion additional people expected to live in cities by 2050.[23] That means there will be even more people who will be exposed to the urban heat island effect. And of course, housing all those new urban dwellers requires developing land, and if forests and natural vegetation are lost in the process, it would only increase the urban heat island effect.

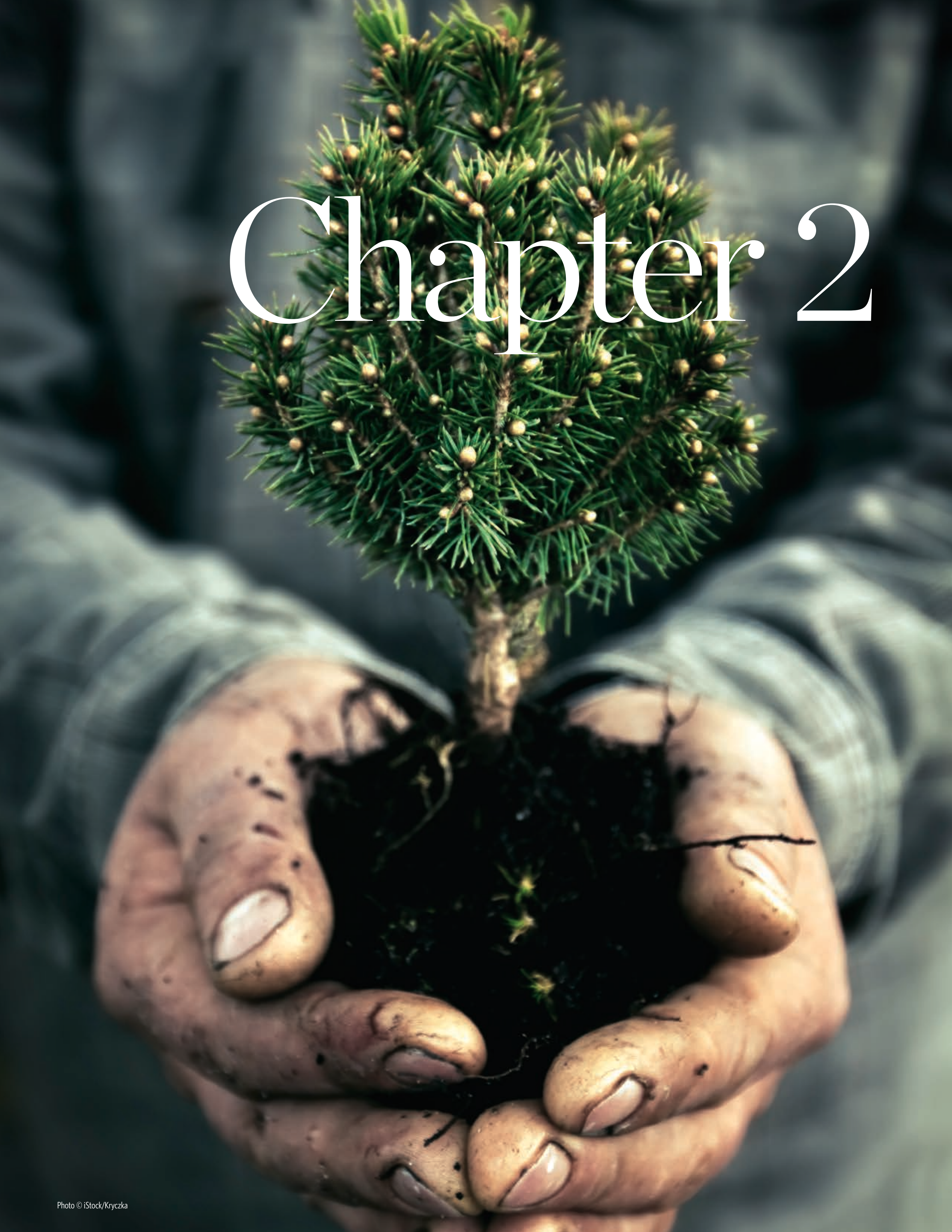
Second, climate change will make heat waves more frequent and more intense. One simple way to see this is to look at projections of the change in average maximum temperatures due to climate change (Map 3). All cities we studied are forecast to have their average maximum temperature increase, although the range is quite large, from roughly 1° C (1.8° F) to more than 4° C (7.2° F). Particularly hard hit seem to be the cities of the Northeast and Midwest of the United States, as well as southern Europe and central Asia.



Map 3. Forecasted increase in annual maximum temperature (˚C) for 2040, compared to the reference period from 1960 to 1990. All global cities in our sample are forecasted to have an increase in annual maximum temperatures of at least 1.5 ˚C (2.7˚F).

More detailed studies have examined the effect of climate change on heat waves in specific geographies. For instance, in the United States, heat wave events that have, on average, occurred every 20 years are forecast to occur by the end of the century every two to four years. These heat waves will not just occur more frequently, they will also be of longer duration, lasting 10 to 20 days longer by century's end.[24] To quote the United States National Centers for Disease Control and Prevention, "What the public now considers to be an exceptional event could become routine across much of the country."[25]

One study by the World Health Organization tried to estimate what this would mean for health. The results are stark (Figure 5). By 2030, annual deaths due to high temperatures could rise to almost 100,000 globally (eight times more than current mortality). By 2050, annual deaths could rise to almost 250,000 (21 times more than current mortality). While these numbers are striking, it is important to realize that it is well within humanity's power to alter these figures. First, decisions made about how much greenhouse gas pollution to allow will control how bad climate change is. It is this uncertainty that is captured in the error bars in Figure 5. Second, the WHO estimates assume no adaptation actions are taken by cities. As discussed in this report, there are many ways smart cities can adapt and prepare for a hotter world.



Chapter 2

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Nature as Part of the Solution

Increasingly, cities are beginning to recognize that nature can be part of the solution to problems of air pollution and excess heat. In this section, we first describe the multifaceted benefits that nature can provide, with a particular focus on the benefits that trees can provide, whether in parks or along streets. We then describe in detail what the scientific evidence tells us about how trees affect particulate matter and ambient temperature. Finally, we discuss the knowledge gaps that remain, and describe how this report is meant to overcome them.

Nature provides many benefits

Nature benefits urban dwellers in many ways (Table 2), and these benefits are often called *ecosystem services*,[26] "the components of nature, directly enjoyed, consumed, or used to yield human well-being."[27] This report focuses on two particular services: the way nature can purify the air and the way it can reduce ambient (outdoor) air temperatures. Nevertheless, any natural intervention supplies a whole portfolio of ecosystem service benefits, and the total value of the whole portfolio must be considered to account for the complete value of the natural intervention.[13]

Ecosystem service	Description
Aesthetic Benefits	The presence of trees and parks increases people's perception of beauty, and thus their happiness. This benefit has monetary value; for example, homes with street trees in front are worth significantly more money.
Recreation	Greenspace is often used for recreation—everything from walking to playing sports to simply relaxing.
Physical Health	Greenspace is used for recreation, and recreation improves people's health.
Mental Health	Research shows that interacting with nature decreases stress and increases focus.
Spiritual value and sense of place	What would New York City be without Central Park? Greenspace often plays an important role in people's spiritual life and appreciation for their city.
Biodiversity	The presence of trees and parks helps provide a habitat for biodiversity.
Erosion prevention	Trees and other vegetation reduce erosion by stabilizing soil.
Stormwater mitigation	Trees and wetlands, whether constructed or natural, can help increase infiltration of stormwater and filter pollutants out of it.
Mitigating flood risk	By slowing the movement of stormwater downstream, trees and wetlands can reduce localized flooding risk. Within floodplains, natural habitat provide a place for floodwaters to go, slowing the movement of floodwater downstream.
Coastal protection	Along coastlines, natural habitats such as mangrove forests offer protection from rising seas.
Air purification (particulates, ozone)	The focus of this report: trees reduce air pollution concentrations.
Shade and heat wave mitigation	The focus of this report: trees reduce ambient air temperatures.

Table 2. Nature in cities has a lot of benefits to those in cities. Above is a listing of common ecosystem service benefits that street trees or parks within cities provide.

There are myriad different ecosystem services, and ecologists often use a simple categorization first used in the Millennium Ecosystem Assessment, which tried to catalog the state of the world's ecosystem services in the early 2000s.[28] One category of ecosystem services is provisioning services—the products people obtain from ecosystems such as food, fuel, or fiber. Ecosystem services in this category are not listed in Table 2, for the simple reason that many provisioning services occur in more rural areas, and their products are then transported to the city center. However, there is burgeoning interest in urban agriculture in many cities, because consumers feel local food tastes better, gives them a greater connection to nature, or is better for the environment.

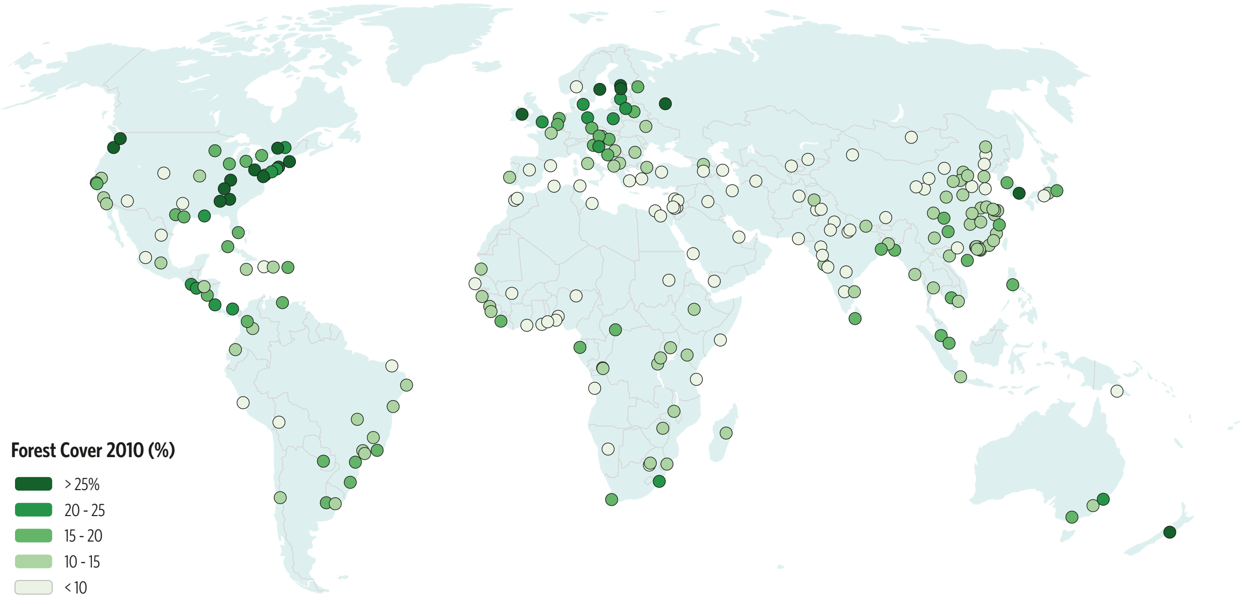
Similarly, one of the most important provisioning services for cities is providing sufficient quantity of water. Municipalities supply water to their residents, who need water for drinking, sanitation, cleaning, and irrigating landscaping, among many other uses. Water is also crucial for energy production, particularly the cooling of thermoelectric plants. Most cities source their water from outside (usually from upstream of) their boundaries, so the maintenance or creation of natural habitat within urban boundaries is unlikely to positively affect urban drinking water provision. It is worth remembering that the strategy of source watershed protection is one commonly used by cities, which one study estimated could have a positive return on investment for more than one in four cities.[29] However, in practice, degradation of source watersheds is widespread and is estimated to cost the world's cities $5.4 billion annually in increased water treatment costs.[30]

Another category of ecosystem services recognized by the MEA is cultural services defined as the nonmaterial benefits people obtain from ecosystems. The aesthetic benefits, for example, of natural areas can be very important to urban dwellers.[13] Whether it is street trees, urban parks, or a view of beautiful mountains, these aesthetics considerations have demonstrated quantified value to the well-being of those in cities. Recreation opportunities for urban residents are another important benefit of urban natural areas, as is the potential value of natural areas near and far as tourist destinations. There are important health benefits urban residents obtain by being near natural areas, including reductions in obesity[31] and increases in mental health.[32] Street trees can also contribute to recreation, by making it more pleasant to work, and can also make a street a more fulfilling and social place, helping build connections among people in the neighborhood.

Another category of the MEA is regulating services, the benefits people obtain from the regulation of ecosystem function. For instance, in riparian systems, natural floodplains play an important role in allowing flood waters to spread out, lessening peak flows and reducing flooding risk in downstream urban areas. Similarly, some natural coastal habitats like wetland, oyster reefs, mangroves, and coral reefs may mitigate the risk of flooding to cities during storms. Many cities are also increasingly using "green infrastructure" or "natural infrastructure" to reduce the amount of stormwater entering city stormwater systems, or to filter out pollutants from stormwater. This ecosystem service has real value for cities that have a regulatory requirement to avoid water pollution.

The purification of the air by trees and the mitigation of air temperatures are also examples of regulating services, ones discussed in detail in the following section. *While we will not mention co-benefits (the other ecosystem services that occur with any natural intervention) much for the remainder of the report, please remember that they occur and can be quite large.* For instance, the National Tree Benefit Calculator, based off the I-Tree software,[33, 34] provides rough first estimates of the economic value of urban trees. In general, the total economic value of a tree is frequently more than 20 times the value specifically for air quality, with stormwater mitigation and aesthetic value for property owners being especially important.

For purification of air and mitigation of air temperature, trees are generally more important than other types of plants (see discussion below). However, the amount of tree cover that cities currently have varies widely, so different cities have different endowments of ecosystem services to start with. Part of this is climatic: In parts of the world where trees are the natural land cover type, a greater proportion of cities also tends to be forested. In contrast, in grassland or desert biomes, unless trees are specifically planted, they will not occur widely (see Box 1 for a discussion of how aridity limits tree planting). Part of the global variation in urban tree cover, however, is a choice. Historically, cities in the United States and Europe have invested more in tree cover,[13] which is reflected in Map 4.

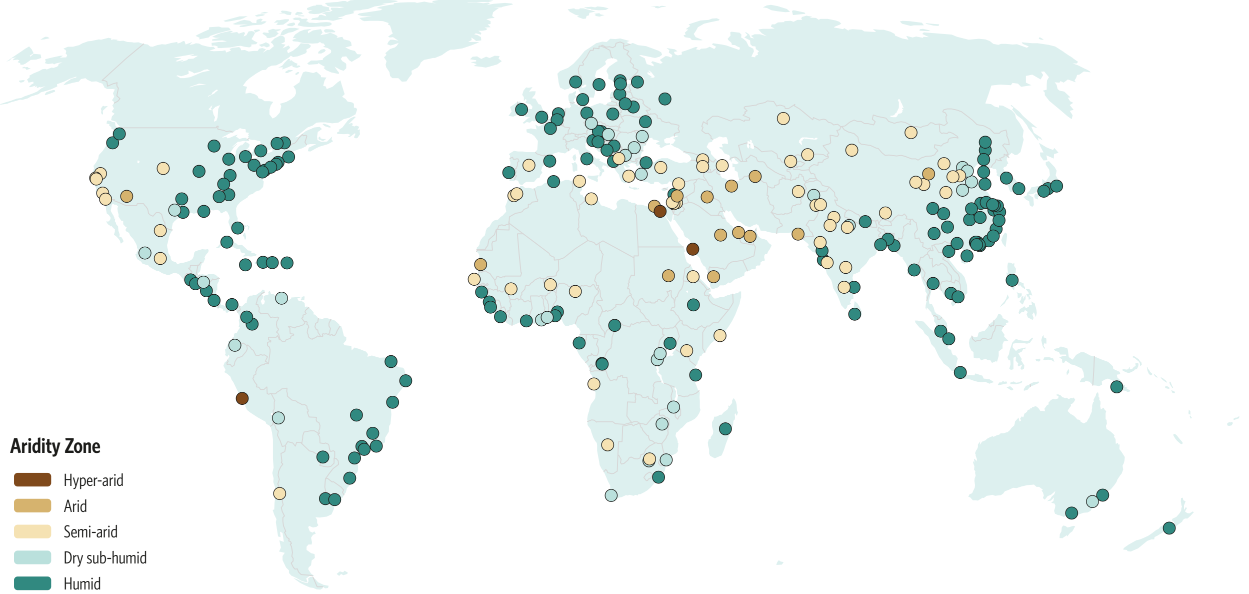


Map 4. The forest cover (%) in cities globally in 2010.

Box 1: Water and limitations on tree planting

This report focuses on trees and the potential they hold for cities looking to clean and cool their air. Of course, many things are needed for tree planting to occur. Space must be available, which can be a challenge in dense urban environments. In our analysis, we have strived to set realistic street tree-planting targets, setting targets for tree cover that at least 5 percent of streets in similar cities already have obtained. Tree planting and maintenance also take money and staff resources, which many cities may struggle to obtain.

Perhaps foremost among the limiting factors in hyper-arid or arid climates is water (Map 5). In these climates, planted trees may require frequent additional water (irrigation) to survive. The amount of irrigation required varies greatly, depending on the tree planted. For instance, in Phoenix (an arid climate), plants like cottonwoods *(Populus* spp.*)* that are adapted to river valleys can consume large quantities of water, whereas some trees adapted to xeric sites, like hackberries *(Celtis* spp.) or acacias *(Acacia* spp.*)*, can have much lower water use. In semi-arid climates, trees may only need irrigation during establishment or during periods of extreme drought, but some level of care is still needed to make sure water use is acceptable. Climate change will potentially also change rainfall patterns in many cities, and should be considered when deciding what trees to plant.



Map 5. The aridity zone of cities in our report.

In this report, we decided to consider all 245 cities in our sample as candidates for tree planting, regardless of their climate zone. We did this since many cities in arid and semi-arid environments do plant trees, and may have sufficient water sources to allow for irrigation of street trees. However, our street tree-planting targets are set based on the tree cover percentage that at least 5 percent of streets in that biome have obtained. This means that our street tree-planting targets are less aggressive in arid environments than in humid environments, reflecting the reality that most arid cities have relatively low tree cover. ***We recommend that all hyper-arid, arid, and semi-arid cities using the results of this report carefully consider the water implications before any new tree planting.***

Trees and air purification

Trees and other natural vegetation affect air quality in several complicated ways. The discussion in this section focuses on the effect of trees on particulate matter. It is worth noting that trees also can mitigate ground-level ozone concentrations under certain conditions,[35] and can also play an important role in absorbing other pollutants.

Conceptually, there are three processes studied in the literature related to PM concentration and trees (Figure 7). First, there is the incoming airflow, which carries a certain concentration of PM (µg/m³). Second, the incoming airflow passes through the canopy, and a fraction of the PM is removed. Note that some fraction of the incoming airflow is deflected instead of passing through the canopy, which can result in locally higher concentrations of PM upwind of a tree. Proper design and location of plantings can ensure that this local concentration does not occur in inappropriate places where it might put people at risk. Third, the cleaner air exits the canopy and continues moving downwind. Over some distance, this cleaner air mixes with other air that didn't pass through the canopy (redilution), and the concentration of PM approaches the average concentration for the region.

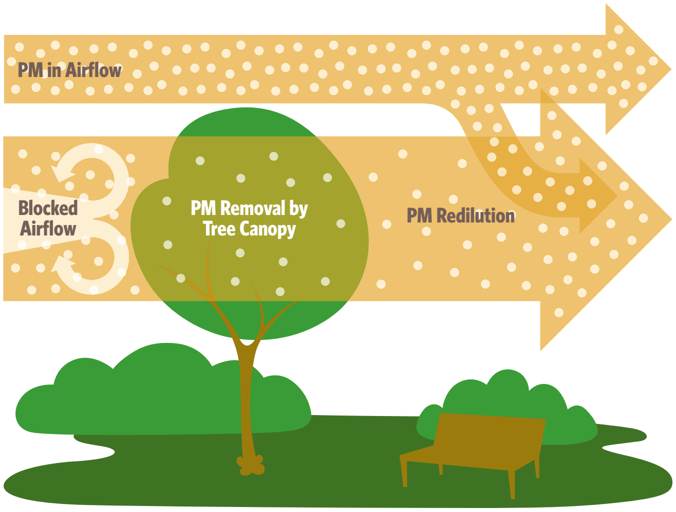


Figure 7. Diagram of PM removal by trees. Illustration: © Mackinzie Jones.

PM removal by tree canopy

PM is removed by plants through a process known as dry deposition. Dry deposition is when particles in the atmosphere deposit themselves on a surface, decreasing the atmospheric concentration of PM.[36] Much of the fine fraction ($PM_{2.5}$) becomes permanently incorporated into leaf wax or cuticle, while a portion of the coarse fraction is resuspended as a function of wind speed.[37, 38] The remainder of the coarse fraction is eventually washed off to the ground by precipitation.[39-42] *It is quite clear from the scientific literature that dry deposition of PM occurs, but studies differ on how much PM tree canopies remove.*

One key parameter controlling how much PM is removed is the concentration of the pollutant: At higher atmospheric concentrations of PM, the rate of dry deposition or absorption is greater. Another is the leaf area: More leaf area offers more surface area on which dry deposition or absorption can take place. Finally, the amount of mixing of the atmosphere matters as well, with better mixing associated with more canopy removal of PM.

As part of this study, we reviewed published literature on trees and their canopy's removal of PM (see Methods). A number of studies[43-49] directly measure the fraction of PM removed by street trees (Figure 8). In this report, we set a Medium impact scenario at the average of reported canopy removal of PM. To capture the uncertainty in this fraction of removal in our global analysis, we set High and Low impact scenarios at ±1 standard deviation from the mean.

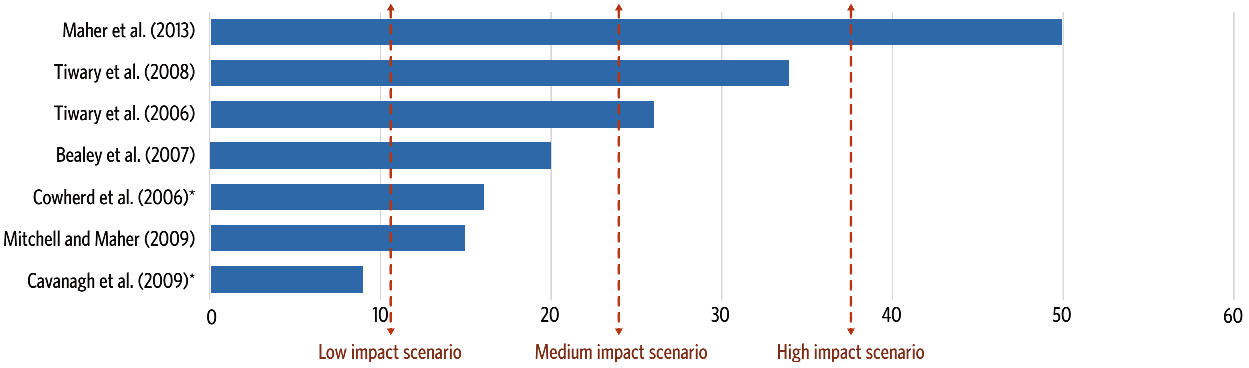


Figure 8. Empirical measures of PM_{10} concentration reduction near urban trees. Dashed lines show the three scenarios of Low, Medium, and High impact used in this global analysis.

Box 2: Deposition velocity box

The literature on dry deposition often summarizes the PM removal rate in terms of deposition velocity (v_d, measured in cm s^{-1}), with greater deposition velocity meaning that overall removal will be greater. Most commonly, studies have measured deposition velocity in closed forest stands or in rural settings. A relatively small number of studies[40, 41, 50] have directly measured deposition velocity in an urban setting.

Measured deposition velocity in cities clearly varies greatly, by species as well as by type of site (Figure 9). This study focuses on roadside vegetation, which our literature review found had a mean deposition velocity of 3.0 cm s^{-1} (see Methods section for more detail). It is interesting to note that commonly used models of PM deposition use PM deposition velocities reported from older, non-urban study sites that generally have lower deposition velocities[43] or from laboratory experiments that may not accurately represent conditions at modeled sites. For instance, many implementations of the Urban Forest Effects model (also called UFORE or i-Tree)[51] are based on the average PM deposition values of Lovett 1994,[52] which was 1.28 cm s^{-1}. This suggests that UFORE and i-Tree estimates may be underestimating removal by roadside vegetation by a factor of 2 or more.

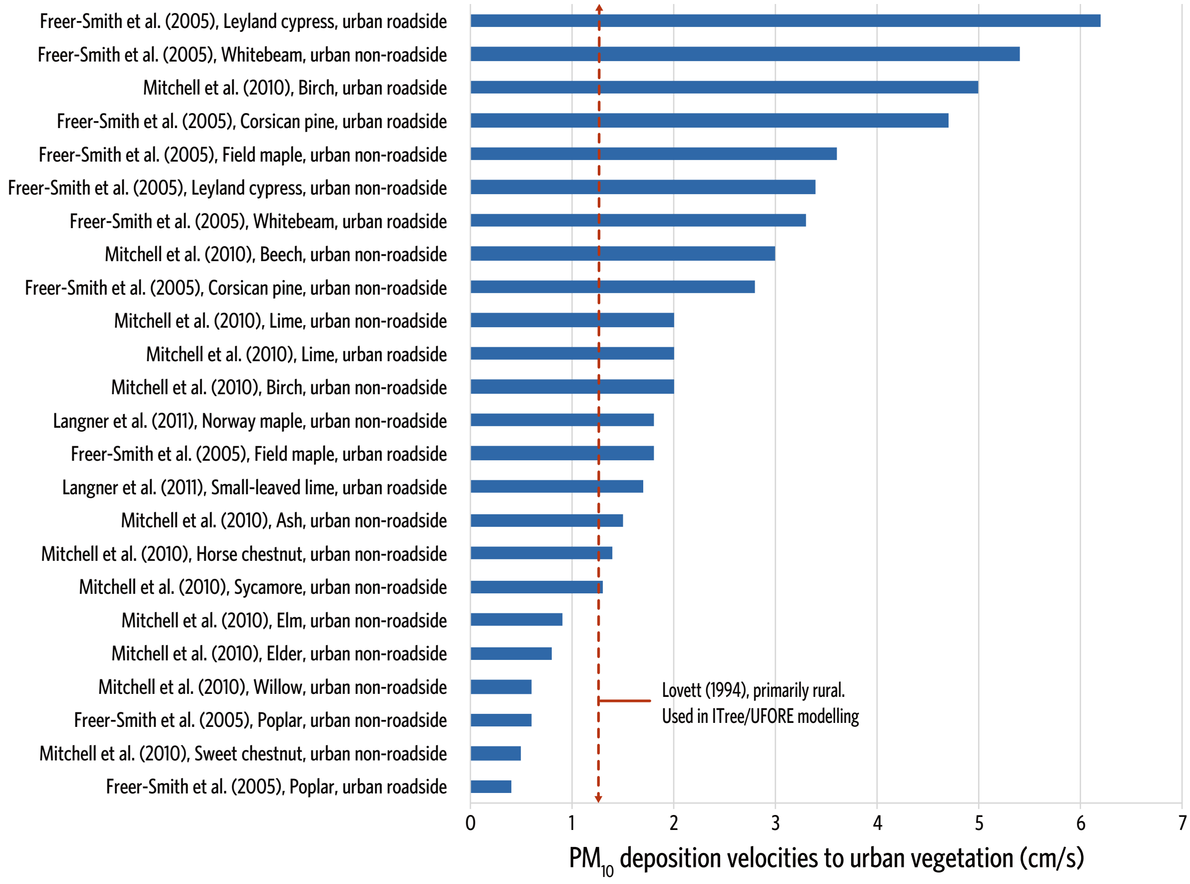


Figure 9. Empirical measurements of PM deposition velocity for urban trees. The dashed line shows the average deposition velocity reported by Lovett (1994), which looked primarily at rural and closed-canopy forests. Note that it is generally lower than the reported value for urban trees. This is notable since Lovett's deposition value is widely used in the i-Tree/UFORE family of models.

There are other reasons to think that some modeled estimates of PM removal in the scientific literature may be underestimates. For example, air pollutant removal models such as the UFORE/i-Tree model[53] generally use ambient pollutant concentrations reported by U.S. EPA air-quality monitors as a key input. Because those monitors are often located away from major emission sources,[54] and because concentrations of PM and many other air pollutants decay to urban background levels over fairly short distances,[55] reported concentrations at monitoring sites may not adequately capture PM variability in an urban area[56] and may underestimate PM levels in areas located closer to emission sources[57] as well as citywide average concentrations.[58] With removal of many pollutants by trees being a linear function of ambient concentrations, all else being equal, such a systematic bias in concentration estimates may result in a substantial underestimate of modeled removal by vegetation in areas near emission sources[44] and citywide average removal.[54]

Given this active discussion in the literature about the appropriate deposition velocity values for use in process-level models of dry deposition, and because the scope of our analysis prevented running such models for all 245 cities in our analysis, we decided to base our PM reduction estimates on empirical measurements of PM reductions in urban settings. Accordingly, we didn't use estimates of deposition velocity directly in our calculation, instead developing the approach described below. Note, however, that Kroeger et al. (in review) compared our methodology to the total removal that would be found using a deposition velocity approach, and found the two methods to give similar ranges of total removal.

Redilution

Our results suggest that tree planting and other vegetative screens have benefits primarily locally. Most reductions in PM concentrations occur within 30 meters, with very little reduction in concentration beyond 300 meters of the installation. This horizontal distance depends on wind speed (advection) and turbulent mixing (diffusion) within the urban canopy layer (approx. up to roof height), which are strongly influenced by urban surface morphology.[59, 60] The number of people who would be affected by a particular planting therefore varies depending on where it is placed, and how many people live close by.

Within this impacted zone, significant reductions in PM are possible. For instance, Maher et al.[43] found that a row of roadside street trees lowered *indoor* PM_{10} concentrations in houses along the street by 50 percent. Mitchell and Maher[44] find that a single tree lowered PM_{10} concentrations behind it by 15 percent; similarly, Bealey et al.[45] found that PM concentrations could be reduced by 20 percent.

Tree planting is but one tool in the toolbox of municipalities seeking to reduce PM concentrations, and should be seen as a complement rather than a replacement to other strategies to reduce PM. *A large body of literature suggests trees can provide localized but meaningful reductions in PM.*

Photo © Kevin Arnold

Box 3: Louisville Green Heart Study

Louisville, Kentucky, is in many ways a study in contrast. Just 15 miles to the south of downtown lies Jefferson Memorial Forest, at 6,500 acres one of the largest urban forests in the country. All told, Louisville boasts more than 120 parks. Manufacturing is booming, and the city has recovered nearly all the jobs lost during the Great Recession. At the same time, Louisville lies in the middle of the "coronary valley:" a multi-state region with twice the national average of cardiac disease and cardiac deaths. Those illnesses carry a $660 million annual price tag. Louisville ranks 17th out of 17 peer cities in air quality, it has the fastest-growing urban heat island in the nation, and it is one of the worst cities in the country to live in if you have asthma. A recent study demonstrated that living in Louisville is the equivalent of living with a smoker for four months out of the year. Compounding the problem has been the loss of tree cover, despite all the parks. One study found that over the last 10 years, Louisville has lost 150 trees per day, or 54,000 per year—equivalent to 800 acres of annual canopy loss. Because of the devastating impacts from a non-native forest pest, the emerald ash borer, and Louisville will lose another 1.5 million trees over the next 10 years. The problems of poor health and loss of tree cover are both particularly severe in economically disadvantaged areas of the city. Reversing tree canopy decline in Louisville, however, will cost hundreds of millions of dollars in the coming decades. The good news is that local communities are looking for ways to reverse the trend of declining tree cover and improve the air they breathe. Scientists are now working hand in hand with these communities to develop strategies that not only could improve the quality of life of Louisville residents, but also could serve as a global model for how urban greenspace can reduce air pollution and, in turn, cardiovascular disease around the world. The Green Heart Project is a six-year agreement between the Nature Conservancy and the University of Louisville School of Medicine, Division of Cardiology, through which the Conservancy will work with local communities to plant trees and other vegetation across Louisville, and University researchers will conduct a ground-breaking longitudinal study to determine the health effects of the neighborhood greening. The project will produce a rigorous evaluation of the link between urban vegetation/greenspace and cardiovascular disease and produce new knowledge relevant to the identification of the environmental determinants of health. The Green Heart Project will focus on establishing a scientific link between trees and neighborhood greenness and human health. Demonstrating such a link in unambiguous terms will help develop new ways to assess the value of the services that nature provides. Proper accounting of these services will catalyze improved public policies that incentivize using nature to achieve better health outcomes and increased public and private investment for conservation projects in cities throughout the world. The study seeks to answer the following key questions:

- What types of plants are best for cleaning and cooling city air? Where and in what amounts would plants be most effective?
- Can nature filter and reduce damaging fine particulate matter and gaseous pollutants from neighborhoods effectively enough to improve health outcomes?
- What is the cost of greening a neighborhood? Can we reduce the healthcare cost (e.g., the rates of hospital admissions and the length of stay) by using nature-based planning tools—thus demonstrating a return on investments in neighborhood greenspace?
- Can we determine how increasing greenspace affects other critical measures of neighborhood health (stress, crime, social cohesion, educational performance, etc.)?
- Can outcomes of this project inform private sector healthcare policy to place emphasis on investing in nature as preventative medicine, thus injecting additional capital for nature?

The Green Heart Project began in January 2016. Researchers developed site selection criteria, identified candidate neighborhoods, and began the design of the clinical study. Key steps were conducting baseline assessments of the candidate neighborhoods' health, air quality, demographics, and eco-system services, and engaging communities in the project. The Conservancy will map the forest cover and species composition of all shade trees in the project area and will work to conserve all ash species in the study neighborhood threatened by the emerald ash borer, as saving trees is less expensive than planting new ones. The Green Heart Project is a unique and unprecedented effort to explore and explain the many links between nature and human health. The extensive data generated by the study will be critical in delineating the contribution of psychological, behavioral, and environmental factors to the relationship between neighborhood greenness and disease risk. The results of this project will also provide a new understanding of how urban greenspaces affect neighborhood livability, community cohesion, economic activity, and geographic resilience.

Trees and temperature reduction

There are two conceptual stages of how trees cool air temperatures (Figure 10). First, depending on the width of the tree canopy, there is a cooling intensity, which is defined as the degree Celsius reduction relative to the average temperature outside the patch. Generally, the larger the canopy the greater the cooling intensity. Second, this cooler air disperses away from the patch, and slowly mixes with other not-cooled air. Generally, the farther from the canopy, the closer the temperature gets to the average temperature in the city.

Cooling intensity

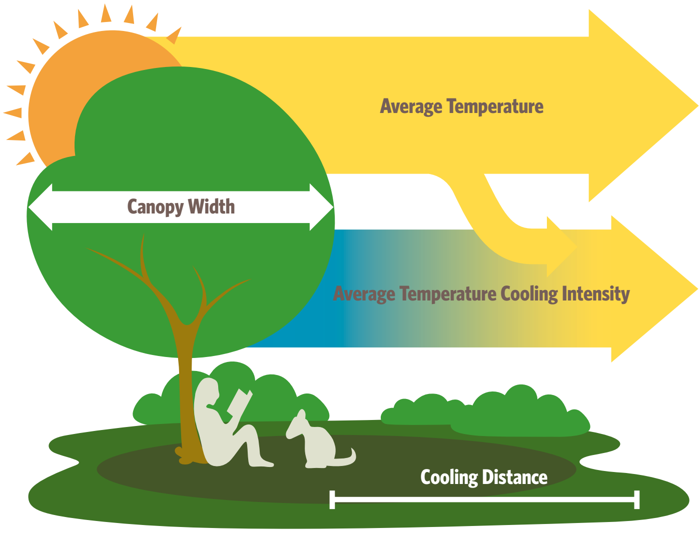


Figure 10. Temperature mitigation by trees. Illustration: © Mackinzie Jones.

Trees and other vegetation can mitigate extreme air temperatures in two ways.[12, 61] First, vegetative cover shades impervious surfaces and prevents the sun's rays from hitting them, thus preventing heat storage (ΔQ_S) and later release, which would contribute to the urban heat island effect. Trees that are tall enough to create a large shaded area under their canopy are more useful than short vegetation. Trees also transpire water as they grow, increasing latent heat storage (Q_E)- essentially some of the sun's energy goes to converting water from its liquid to vapor form (latent heat), rather than increasing air temperature (sensible heat). From the perspective of mitigating extreme temperatures, this latent heat storage is a good thing since it prevents an increase in air temperature, although in some dry climates the loss of water from planted trees may put a strain on scarce water supplies.

Both the transpirative cooling[62] and the shading effect[63] of trees individually can substantially lower maximum summer daytime air temperatures in streets at pedestrian level. However, shading of sealed surfaces under tree canopy has a particularly critical effect on pedestrian thermal comfort because it dramatically lowers surface temperatures[64, 65] and the mean radiant temperature to which pedestrians are exposed.[e.g., 63, 65-67] Mean radiant temperature is a function of the heat fluxes (short and longwave radiation) a body receives from surrounding surfaces[68] and is the key temperature component determining human thermal comfort in summer.[68-70]

The intensity of the cooling effect of urban trees can vary substantially among tree species[71, 72] and with tree size as a result of differences in foliage density and leaf area index (LAI), leaf thickness, orientation and light permeability, and photosynthetic and water use rates. Cooling intensity shows a strong positive relationship with canopy area and density.[e.g., 71, 73]

The summer daytime cooling effect of individual trees, street trees or larger treed areas has been quantified in a large number of experimental studies in temperate, subtropical, and tropical regions.[74] There are a large number of studies that look at urban parks (see Methods section for a list), but because this report is focused on street trees, we based our study on direct estimates of cooling intensity of street trees[62, 64, 65, 70, 75-79] (Figure 11). Cooling intensity varies from 0.4° C (0.7° F) to 3.0° C (5.4° F) depending on the site and the time of day. In this report, we set a Medium impact scenario at the average of reported cooling intensity. To capture the uncertainty in the intensity of cooling in our global analysis, we set High and Low impact scenarios at ±1 standard deviation from the mean.

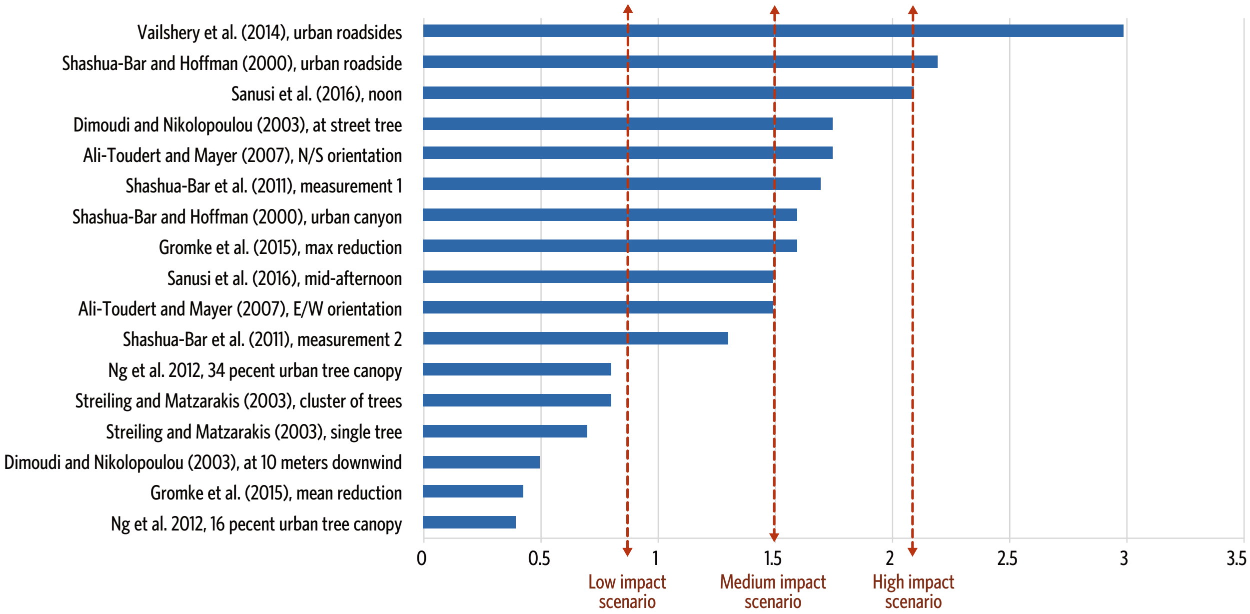


Figure 11 . Empirical measures of temperature reduction near urban trees. Dashed lines show the three scenarios of Low, Medium, and High impact used in this global analysis.


Photo © Alija

Cooling distance

In our literature review, we paid special attention to the spatial zone over which cooling occurs. The cooling effect extends into surrounding areas primarily through advection[80, 81] with its reach a positive function of canopy area but mediated by airflows and temperature gradients with surroundings.[71, 80] Most studies find that the maximum cooling distance of urban forest patches or partially forested parks on sunny summer days extends to approximately one park width from the park,[82, 83] though shorter or much longer,[70, 73] distances are possible. For street trees, the likely effect on temperatures is strongest within 30 meters of a tree.

As in the case of PM mitigation, tree planting should be seen as complementary tool to other ways to reduce ambient air temperature, rather than a replacement. A large amount of literature suggests trees can provide localized but meaningful reductions in temperature.

The goals of this report

As the above review of the literature shows, there is evidence that trees and other vegetation could play a role in cooling and cleaning city air, helping to make cities healthier and more pleasant places to live. There are currently several studies and existing models that measure the ability of individual trees or forest stands to capture pollutants and cool city streets, but the scope of this conservation strategy is still unknown. The core idea of this report is that despite the scientific literature, it remains difficult for government agencies, health officials, municipal staff, and foundations to assess whether it is worthwhile to consider nature as part of the solution to the problems of particulate matter pollution and excess heat. Our hope in launching work on this report was that a systematic application of existing data to a broad set of cities can show us *how much nature is needed* to make a difference.

Major questions that guided our research were the following:

- What fraction of the air-quality problem can vegetation solve?
- Which cities can natural infrastructure help the most?
- How much vegetation is enough to achieve meaningful health benefits?
- How much investment, in dollar terms, is needed?
- Where is natural infrastructure a cost-effective investment, relative to common built infrastructure alternatives?

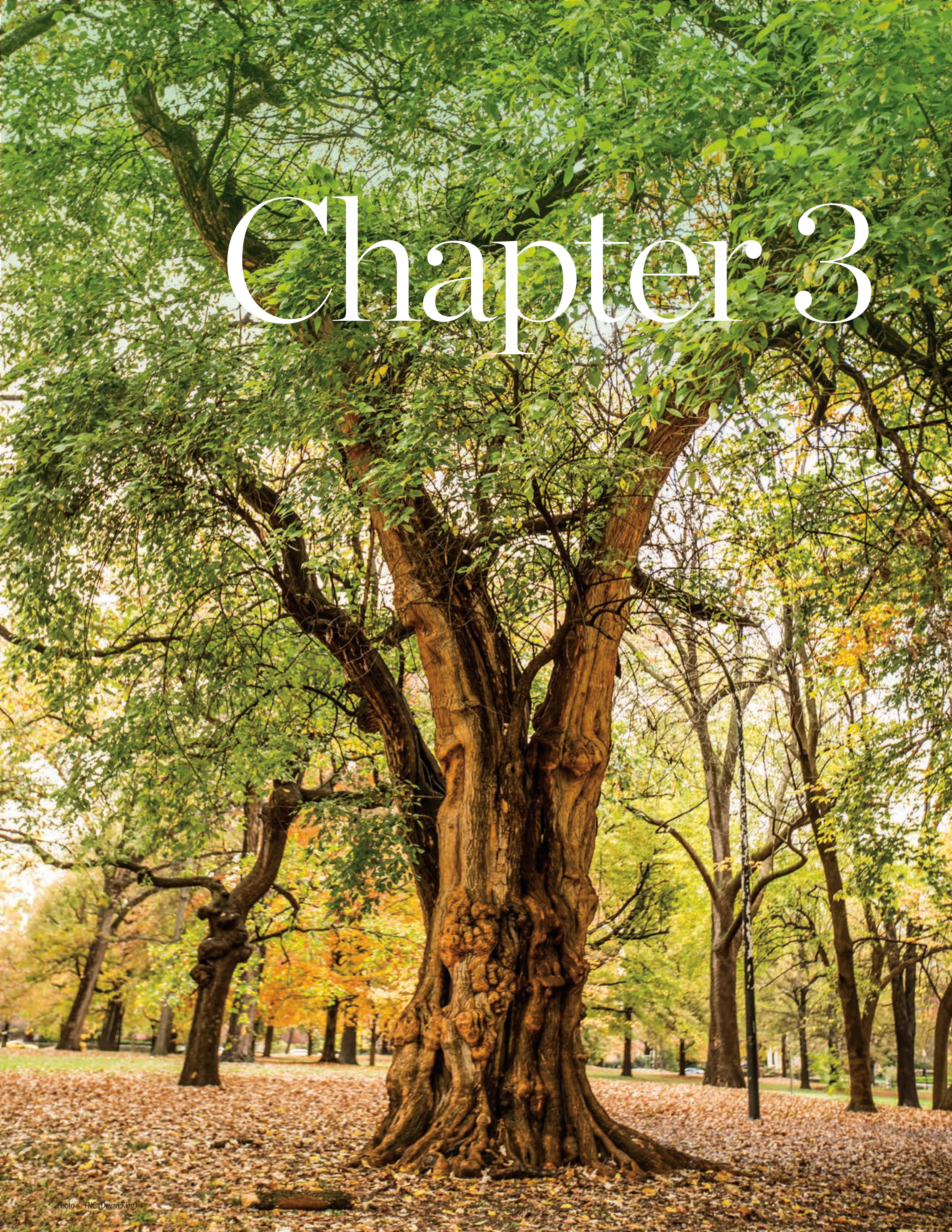
The Nature Conservancy conducted—in coordination with C40—the first global survey of cities designed to quantify the potential role for nature in making air cleaner and cooler. We collected geospatial information on forest and land cover, $PM_{2.5}$ pollutant concentration, and population density for 245 cities, and then used established relationships in the literature to estimate the scope of current and future trees to make urban air healthier. These 245 cities currently house around 910 million people, or about a quarter of the world's urban population.

Investing $100 million

annually in tree planting could provide 77 million people with cooler cities and 68 million people with cleaner air.

Photo © iStock, Sean Pavone

Chapter 3



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The Importance of Targeting

Trees already are providing large benefits

The current stock of trees in our study cities is already delivering real reductions to $PM_{2.5}$ (Table 3). We estimate that trees are currently providing on average 1.3 million people at least a 10 µg/m^3 reduction, primarily in cities that have high ambient concentrations of $PM_{2.5}$. This is the estimate for our Medium removal scenario, which represents the central estimate of deposition velocities from the literature. However, there is uncertainty in this parameter, which we consider by looking at Low and High removal scenarios. In the Low scenario, no one is getting at least a 10 µg/m^3 reduction, while in the High scenario there are 6.1 million people getting at least a 10 µg/m^3 reduction. Similarly, we estimate that 10.2 million people (1.0 to 15.4) have at least a 5 µg/m^3 reduction due to the current trees in their city, and 52.1 million people (23.8 to 63.1) at least a 1 µg/m^3 reduction in $PM_{2.5}$.

	Population (millions)			Proportion of urban population (%)		
	High	Medium	Low	High	Medium	Low
> 10 µg/m^3 reduction	6.1	1.3	0.0	0.7%	0.1%	0.0%
> 5 µg/m^3 reduction	15.4	10.2	1.0	1.7%	1.1%	0.1%
> 1 µg/m^3 reduction	63.1	52.1	23.8	6.9%	5.7%	2.6%

Table 3. The current reduction in PM that trees provide. Population is the total population across our sample of 245 cities, while the proportion is calculated relative to the 912 million people who live in those cities. Information is shown for our three scenarios (High, Medium, and Low), which describe different effectiveness in trees reducing PM.

For temperature, we estimate that the current stock of trees in our study cities is already providing 68.3 million people with a 1.0° C (1.8° F) reduction in summer maximum air temperatures under our Medium scenario (Table 4). There is some uncertainty about the magnitude of the reduction provided, which is captured in our Low and High scenarios.

	Population (millions)			Proportion of urban population (%)		
	High	Medium	Low	High	Medium	Low
> 2°C reduction	68.3	0.0	0.0	7.5%	0.0%	0.0%
> 1°C reduction	68.3	68.3	0.0	7.5%	7.5%	0.0%
> 0.5°C reduction	68.3	68.3	68.3	7.5%	7.5%	7.5%

Table 4. The current reduction in temperature that street trees provide. Population is the total population across our sample of 245 cities, while the proportion is calculated relative to the 912 million people who live in those cities. Information is shown for our three scenarios (High, Medium, and Low), which describe different effectiveness in trees reducing temperature.

We also assessed trends over time in urban forest cover (Figure 12). We found that 26 percent of cities had a decline in forest cover over the period from 2000 to 2010, whereas only 16 percent of cities had an increase in forest cover over the time period. More than twice as many cities had a large loss in forest cover (defined as > 5 percent change in forest cover) than had a large gain. Perhaps it isn't surprising that the general direction in many cities is toward a decline in forest cover, since cities continue to grow, and new development sometimes displaces trees.

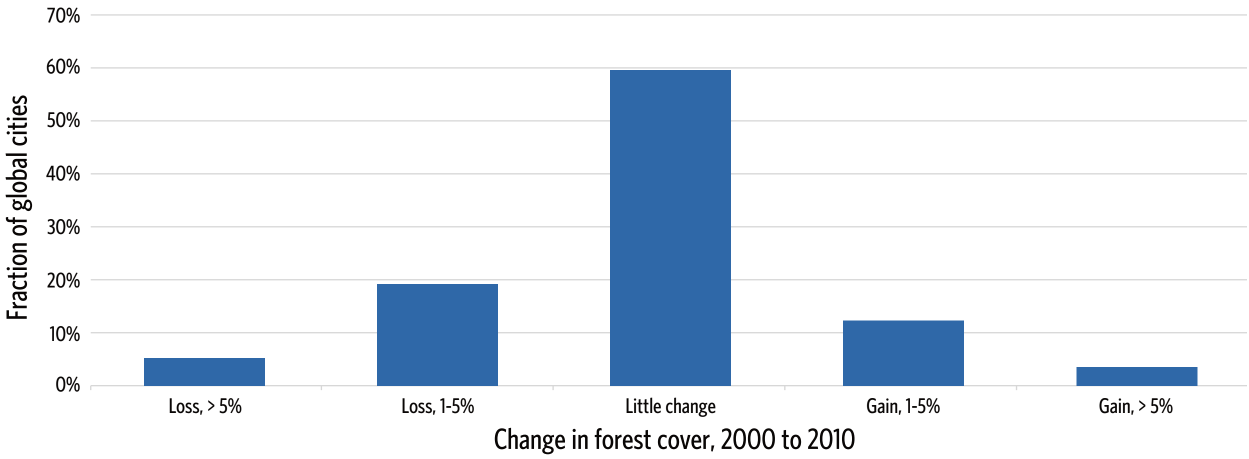
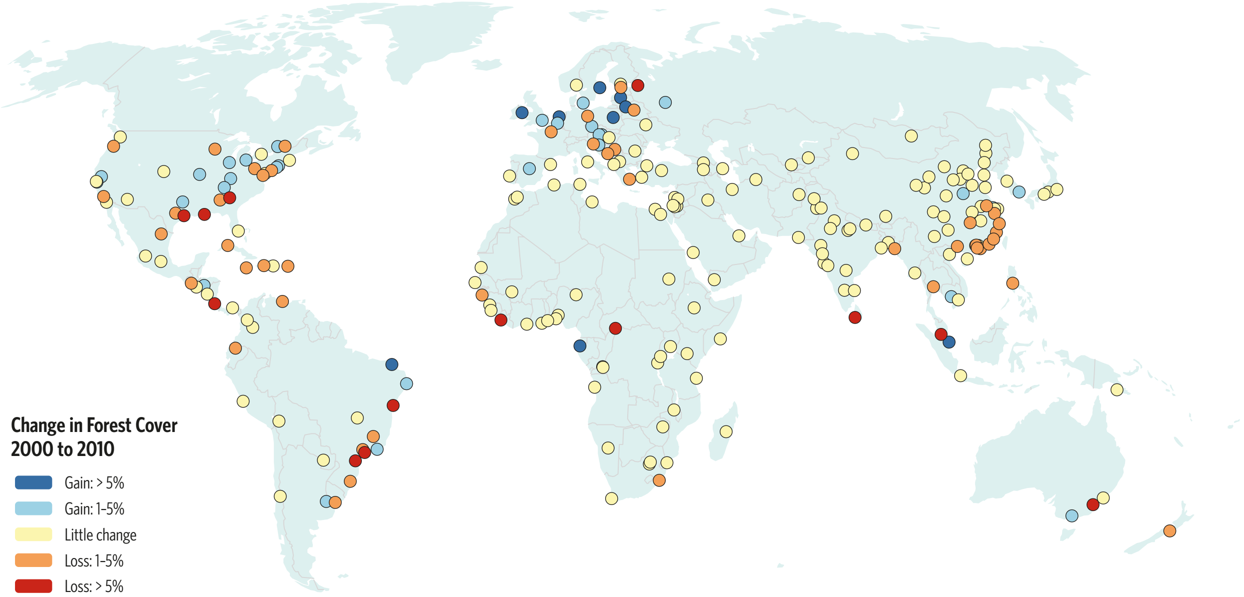


Figure 12. The fraction of global cities in our sample (N=245) that have a loss or gain of forest cover, from 2000 to 2010. Roughly one in four cities had either a small loss (19 percent of cities) or large loss (5 percent of cities). The majority of cities (60 percent) had relatively little change in forest cover.

However, this average decline in forest cover masks significant variation among cities (Map 6). Many cities in Northern Europe and parts of the United States appear to have gained in forest cover. In contrast, other parts of the world had cities that generally lost forest cover, such as southern Europe and the south of the United States.



Map 6. Change in forest cover from 2000 to 2010, for cities globally. Change is calculated as percent change between the two time periods, (Cover2010 – Cover2000)/Cover2000. For instance, a city that has had a 5 percent decline has had a loss of 1 in 20 (5 percent) of its trees.

Those cities that are losing forest cover are also losing ecosystem service provision from those trees, whether their aesthetic beauty or their ability to clean and cool the air. While we didn't explicitly estimate that loss of ecosystem service provision in this report, cities that are losing canopy cover should expect some negative impact on air quality and ambient air quality.

Box 4: Pests and pathogens

Urban trees face significant threats from invasive insects and pathogens, many of which have moved around the world through global trade. These pests and pathogens can spread rapidly through multiple pathways such as transportation of nursery stock and the movement of infested or diseased firewood.

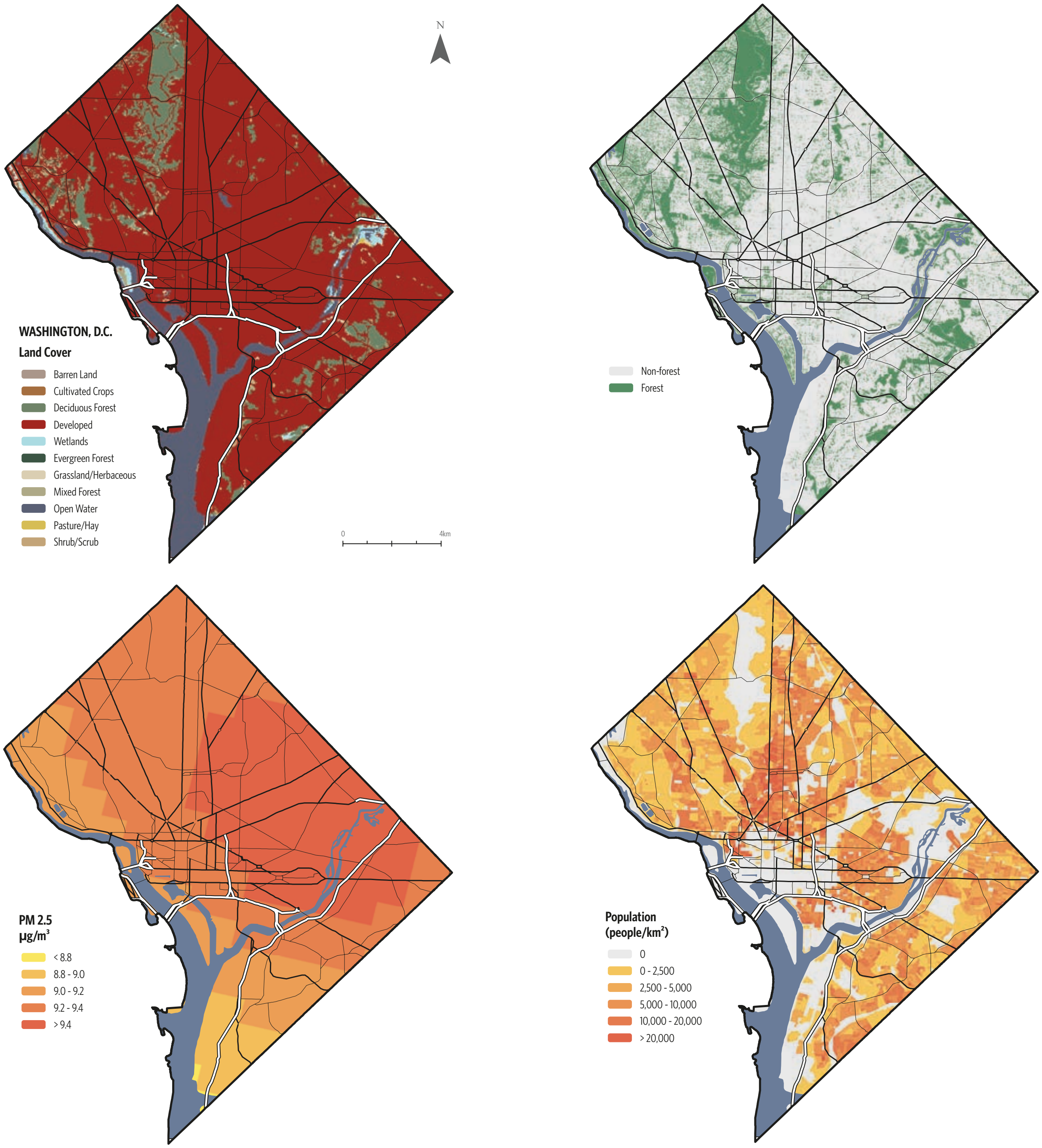
In the United States, particularly damaging invasive insects and pathogens have led to considerable decline of iconic American tree species such as elms *(Ulmus* spp.*)*, chestnuts (*Castanea* spp.*)*, and most recently, ashes *(Fraxinus* spp.*)*, especially across the Northeastern and Midwestern United States. While federal and state resources are available initially, as an infestation or epidemic matures and as these trees die—in some cases rapidly, others over the course of two or more years—the burden of management becomes a municipality's for trees on public property, or a homeowner's for trees on private property.[84] The limitations of municipal tree budgets and the at-times prohibitive costs of tree removals for homeowners has created a deficit in the level of response needed to significantly reduce the risk to people and property, posed by dead or decaying trees.

A number of strategies can prevent or slow the spread of tree pests and diseases. For example, stricter border control mechanisms can prevent the importation of diseased/infested plant material and packaging. Additionally, the public can being trained on how to identify and report the initial signs of pest or disease presence on the trees in their community, which gives forest managers the opportunity to rapidly respond and potentially limit canopy loss.

Emerald ash borer. Credit: US Forest Service

The importance of targeting—within cities

Our results suggest that targeting—putting trees in the right places to benefit people—is key. Within cities, there is substantial variation in the driving variables that affect the ability of trees to remove particulate matter or mitigate ambient air temperatures. For instance, in Washington, D.C., patterns of land use change from neighborhood to neighborhood (Map 7). The city's geography is dominated by two rivers, the Potomac and Anacostia, that merge and flow south to the Chesapeake Bay. A large protected area, Rock Creek Park, runs north-south in the city. Neighborhoods to the west of this park are generally at lower population density, and have higher tree cover, than neighborhoods east of the park. Particulate matter concentrations, by contrast, are highest north and east in Washington, D.C. Population density is also highest in these neighborhoods. In contrast, the center of the city, along the National Mall and the Capitol Building, residential populations are near zero.



Map 7. Driving variables that affect the calculated return on investment (ROI) of tree planting, for one city, Washington, D.C.

In our study, we pulled together the most detailed information possible for 27 U.S. cities and seven Chinese cities. For this set of "calibration" cities, we also created high-resolution (2-meter) maps of forest cover. Our goal with the calibration analysis was to understand how important these fine-scale patterns were. Then, for all 245 cities in our global analysis, we assembled the best globally available data for analogous data layers. We took this two-step approach because it was not logistically feasible to develop high-resolution data sets for all 245 cities in our global analysis.

For instance, for forest cover we used 30-meter forest cover estimates derived from Landsat imagery for our global analysis. We compared the results for the calibration cities against the results for our global analysis in order to develop scaling functions. High-resolution forest cover estimates are statistically correlated with the lower resolution Landsat-derived forest cover estimates (Figure 13). What this means is that for our global analysis, we can statistically correct for any biases present in the lower-resolution data (see Methods appendix for details).

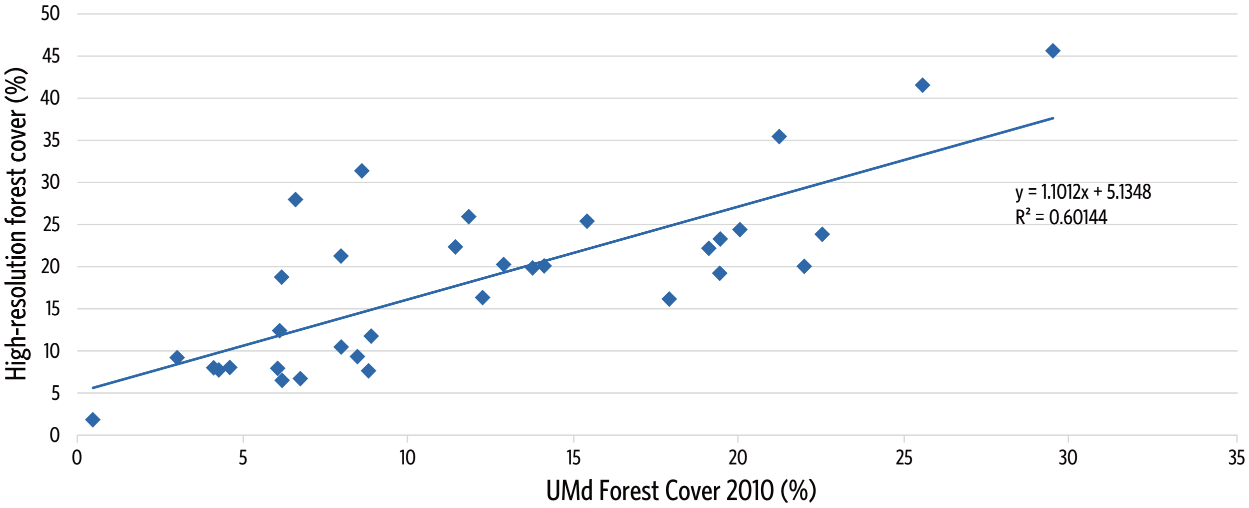
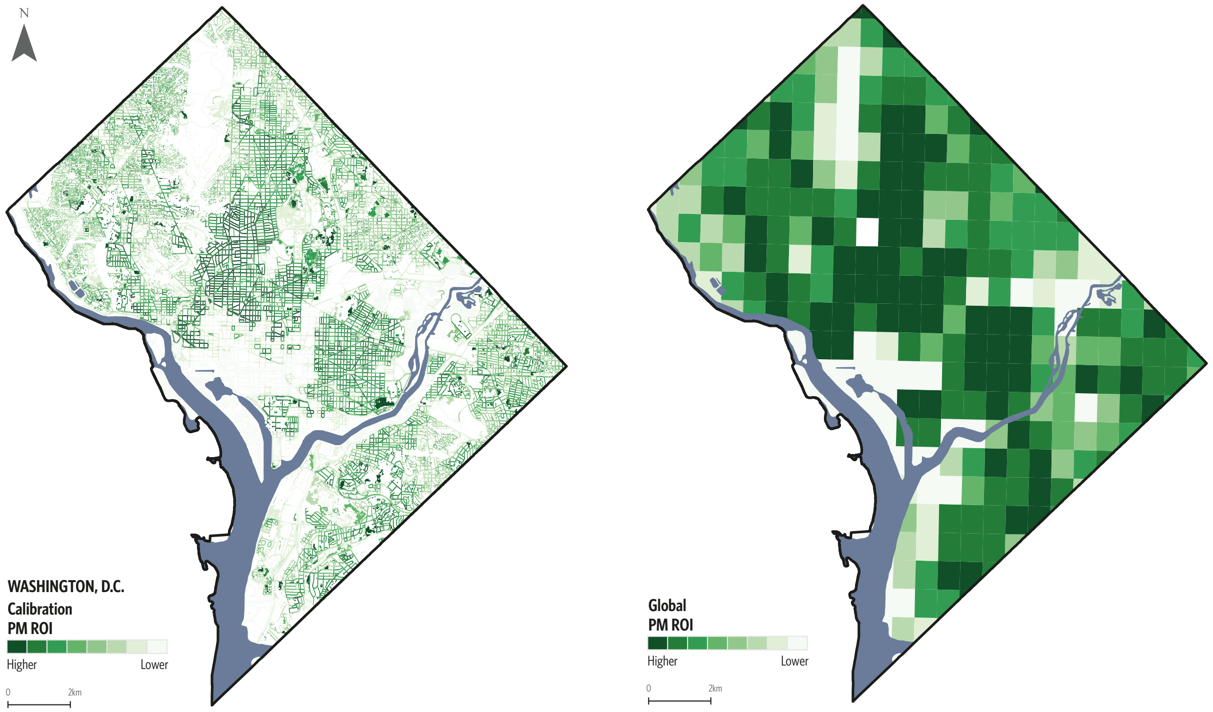


Figure 13. In 34 calibration cities, we developed high-resolution 2-meter forest cover maps that can accurately measure street tree cover. This high-resolution information is not available for most cities globally, and for our global analysis of 245 cities we used 30-meter estimates of percent forest cover, derived from Landsat imagery. However, forest cover as estimated at the two resolutions is correlated, so using the globally available data, we can calculate an accurate estimate of "true" tree cover.

Using all these input layers, we then built a model to estimate the return on investment (ROI) of tree planting, in terms of its impact on particulate matter or ambient air temperature. Please keep in mind that while we focused our ROI analysis on two services (reduction in PM and temperature), trees provide a multitude of other benefits that may be of great value, as well.

Our results show substantial variation within cities, with the best neighborhoods for natural infrastructure investment often having two orders of magnitude greater ROI in tree planting than the least suitable neighborhoods. Targeting the neighborhoods with the highest mitigation impacts becomes crucial (Map 8). Generally, for PM, those neighborhoods are characterized by higher population density and thus more people who will benefit from cleaner air. They are also characterized by higher concentrations of $PM_{2.5}$ and concomitant higher PM removal by trees.



Map 8. Spatial patterns of estimated return on investment of planting street trees to reduce PM, for Washington D.C. The top panel is from a detailed, street-level "calibration" calculation we conducted for 35 cities globally. The bottom panel shows the "global" analysis that we conducted for 245 cities globally, where the minimum mapping unit is a 1 km^2 neighborhood. Results are highly correlated, giving us confidence that our global analysis is capturing the major spatial patterns in each city.

Map 8 compares the ROI estimates for particulate matter removal from our calibration analysis (left panel) and our global analysis (right panel) for Washington, D.C. Note that while the ROI estimates are, of course, more spatially detailed in the calibration analysis, the general neighborhood-level pattern of where you would want to invest is captured by the global analysis. Generally, the neighborhoods with the highest ROI of investment are in the higher-density neighborhoods east of Rock Creek Park, which also have some of the higher concentrations of particulate matter. They are also the neighborhoods with some of the lowest current tree cover, so they have relatively low current ecosystem service provision.

There are similar neighborhood-level patterns in ROI of tree planting for air temperature mitigation, with ROI varying among neighborhoods by two orders of magnitude. The ideal high-ROI neighborhood would have high population density (or a concentration of sensitive populations) leading to larger number of people benefiting from heat reduction by trees. Higher-population density neighborhoods generally score higher, simply because any reduction in ambient air temperature benefits a larger group of residents. *See the Case Study section below for neighborhood-level maps of ROI for 15 major global cities, or check out the website for this report* nature.org/healthyair*, which presents geospatial information for all cities considered in this report.*

Our review of the literature suggests that sensitive sites, such as schools and hospitals, should also be a focus of targeting. Because populations (young children or the elderly) that use these sites are most likely to suffer negative health effects from air pollution or high temperature, it makes sense to concentrate tree planting around these facilities. Young children, for instance, are especially sensitive to asthma, while the elderly are at increased risk of negative health impacts from exposure to extreme heat. In our global analysis, we estimated how much tree planting could help schools and hospitals globally, drawing on (incomplete) maps of these facilities present in the Open Street Map.

	Proportion of schools (%)			Proportion of hospitals (%)		
	High	Medium	Low	High	Medium	Low
> 10 µg/m³ reduction	1.3%	0.2%	0.0%	1.8%	0.0%	0.0%
> 5 µg/m³ reduction	5.0%	1.9%	0.1%	9.0%	3.1%	0.0%
> 1 µg/m³ reduction	91.6%	73.3%	21.2%	89.9%	74.4%	31.9%

Table 5. The maximum reduction in PM that street trees could provide to schools and hospitals. Information is shown for our three scenarios (High, Medium, and Low), which describe different effectiveness in trees reducing PM.

Table 5 shows the potential reductions in particulate matter that additional new tree planting could cause in the ambient air concentrations just around the facility. Only a small fraction (less than 2 percent of facilities globally) could have large reductions, defined as greater than a 10 µg/m³ reduction in concentration of $PM_{2.5}$. These large reductions mostly occur in cities with currently high levels of $PM_{2.5}$. However, around nine in 10 schools and hospitals could get a modest reduction, greater than a 1 µg/m³ reduction. Similarly, trees have the potential to deliver a modest temperature reduction of 1° C (1.8° F) to more than nine in 10 schools and hospitals globally, under our Medium scenario (Table 6).

	Proportion of schools (%)			Proportion of hospitals (%)		
	High	Medium	Low	High	Medium	Low
> 10 µg/m³ reduction	1.3%	0.2%	0.0%	1.8%	0.0%	0.0%
> 5µg/m³ reduction	5.0%	1.9%	0.1%	9.0%	3.1%	0.0%
> 1 µg/m³ reduction	91.6%	73.3%	21.2%	89.9%	74.4%	31.9%

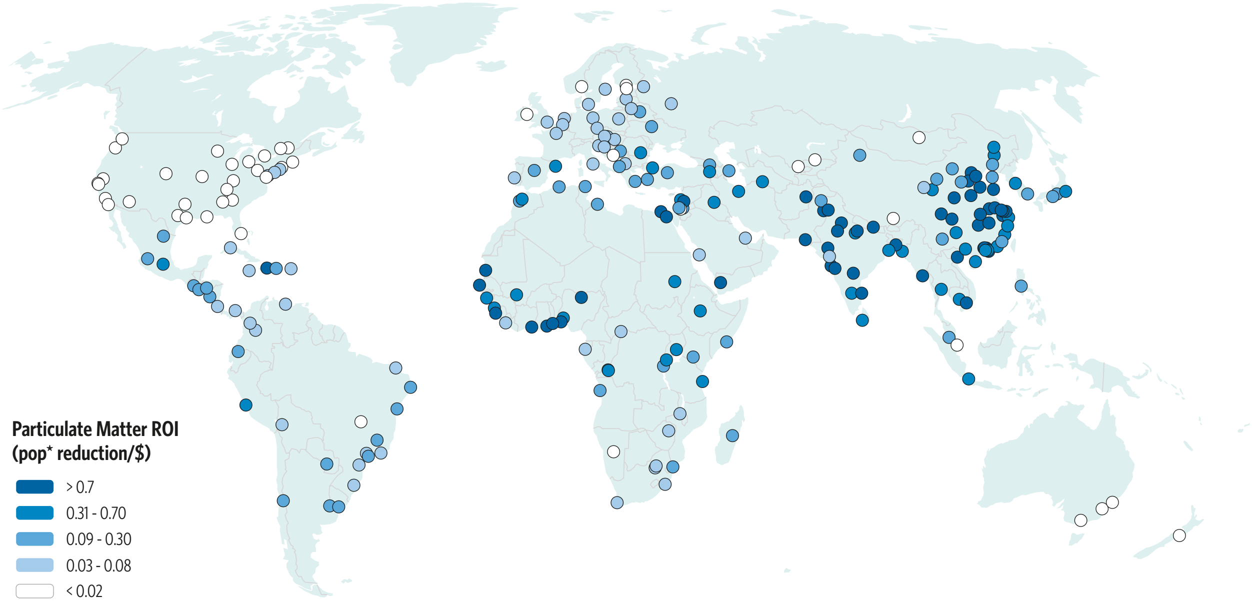
Table 6. The maximum reduction in temperature that street trees could provide, if streets were planted up to a reasonable target density. This maximal scenario would involve an annual investment of $3.2 billion and would benefit to some degree 220 million people, so around $15 per person. In the table below, population is the total population benefited across our sample of 245 cities, while the proportion is calculated relative to the 912 million people who live in those cities. Information is shown for our three scenarios (High, Medium, and Low), which describe different effectiveness in trees reducing temperature.


Photo © iStock, JoelCarillet

Photo © iStock, natbits

The importance of targeting—among cities

There is also substantial variation among cities in the potential for trees to reduce particulate matter (Map 9). Cities with high population density generally have higher median ROI, as do cities with higher concentrations of particulate matter. An additional factor that varies among cities is the cost of tree planting; all else being equal, cities with lower tree planting and maintenance costs have higher ROI. Generally, cities in East and South Asia have the highest median ROI of tree planting, as well as cities in West Africa. The United States and Europe score lower in terms of median ROI, simply because their particulate matter concentrations are already low by global standards. Note, however, that the substantial variation in ROI within cities means that *in almost any city, neighborhoods can be found with a high ROI of tree planting.*



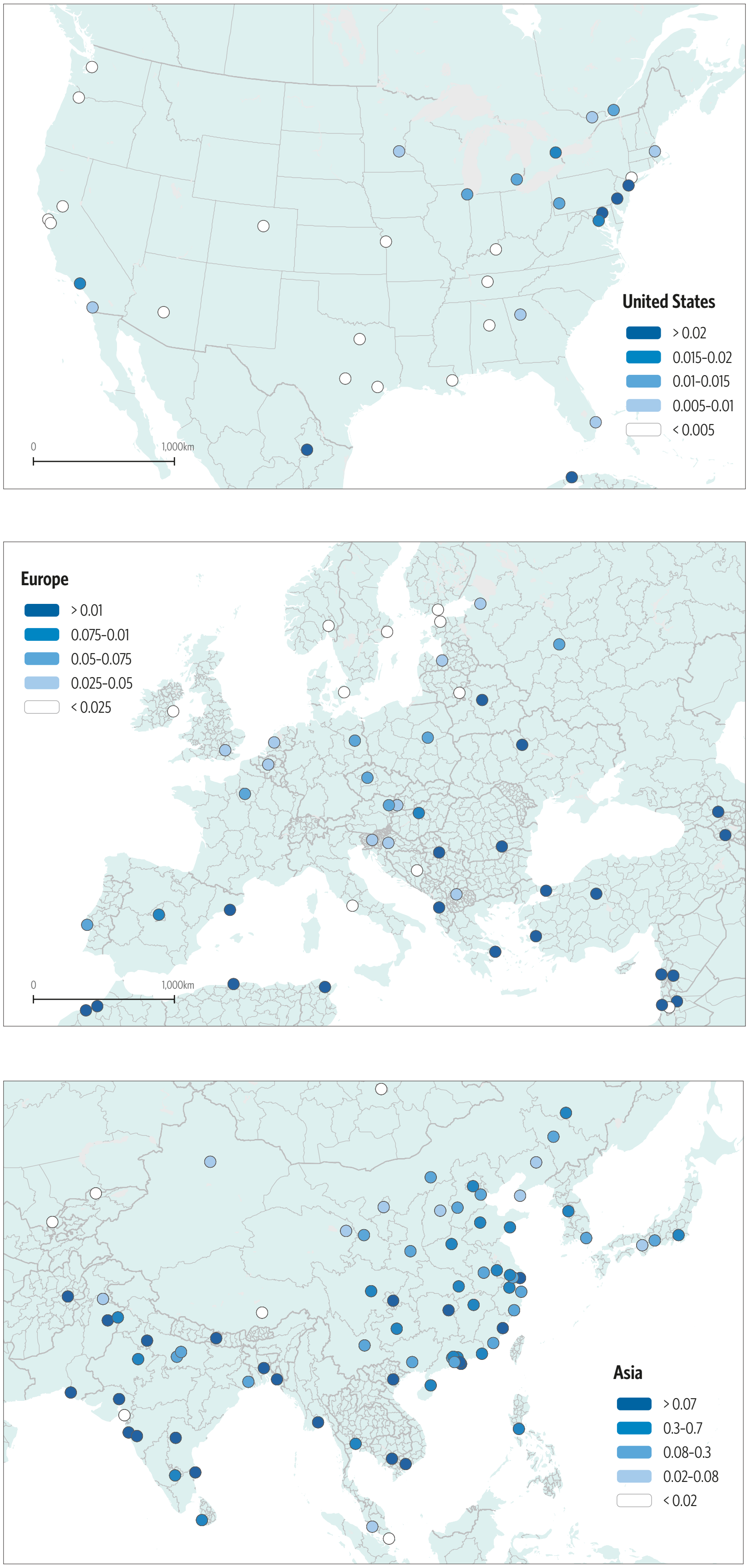
Map 9. The median return on investment (ROI) of planting street trees to reduce PM, as expressed in the reduction of $PM_{2.5}$ (µg/m^3) multiplied by the number of people who see that reduction, divided by costs (USD$). ROI is calculated for our Medium scenario, for a hypothetical small planting of a 50-meter street segment. Cities with higher population densities, higher ambient concentrations of $PM_{2.5}$, and lower planting costs have higher median ROI. Note that there is significant variation in potential ROI within cities, so most cities have neighborhoods within them with high PM ROI.

The large global range in median ROI makes it hard for one figure to show all the variation among cities. Maps of specific regions can also show interesting and important variation in median ROI (Map 10). Within North America (top panel), the high-density cities in the Northeast of the United States, such as New York, Philadelphia, and Baltimore, have relatively high median ROI from trees for PM reduction. Other cities that are relatively high density in Canada, such as Toronto and Montreal, have relatively high median ROI.

Within Europe (middle panel), there is a general trend for cities in eastern Europe having higher ROI for PM mitigation than cities in western Europe, driven primarily by generally higher population density and concentrations of PM in the east. In contrast, northern European cities have relatively low ROI, in part because they have lower PM concentrations. Population density matters, as well, with large capital cities like Paris and Madrid having relatively high ROI.

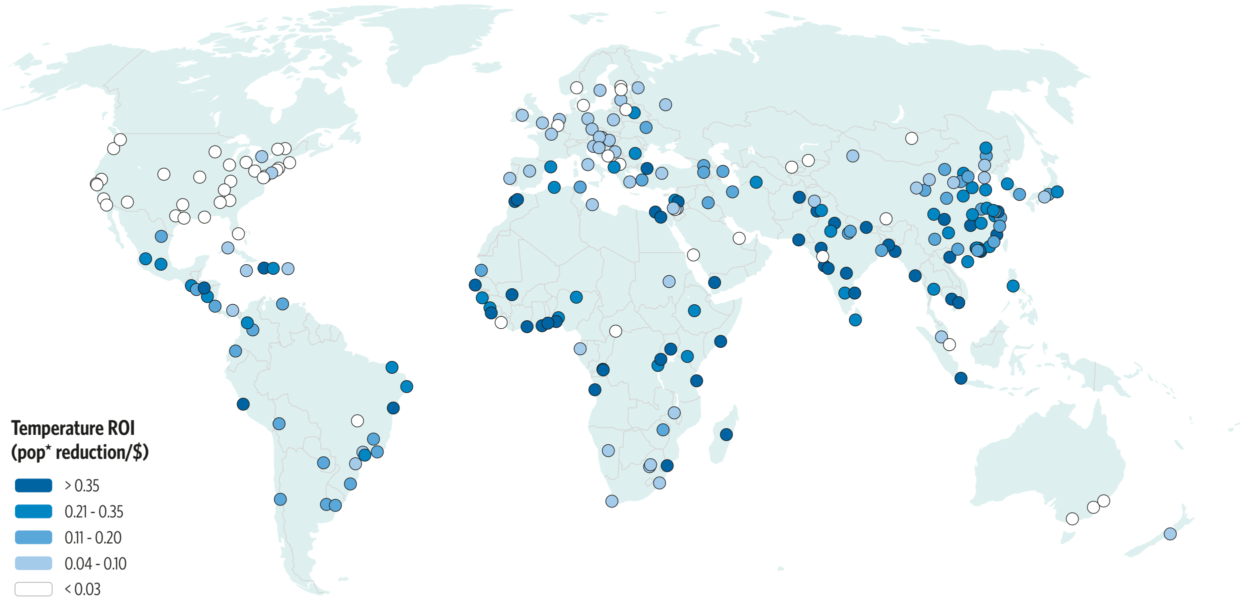
Within Asia (bottom panel), Indian and Chinese cities have some of the highest ROI from tree planting for PM mitigation. Cities in Central Asia, by contrast, have lower population density and thus lower ROI.

Particulate Matter ROI (pop* reduction/$)



Map 10. Regional patterns of ROI of planting street trees to reduce PM, expressed as median ROI.

The same factors drive large variance in ROI of tree planting for temperature mitigation among cities (Map 11). Not surprisingly, therefore, the Map 12 median ROI by cities looks similar for PM and temperature. However, cities in South America score relatively higher for the ROI of temperature mitigation than they do for PM mitigation. *Again, substantial variation within cities means even in the United States and Europe, there are neighborhoods in most cities with high ROI of tree planting for temperature mitigation.*



Map 11. The median return on investment (ROI) of planting street trees to reduce ambient air temperatures, as expressed in the reduction of air temperature (˚C) multiplied by the number of people who see that reduction, divided by costs (USD$). ROI is calculated for our Medium scenario, for a hypothetical small planting of a 50-meter street segment. Cities with higher population densities and lower planting costs have higher median ROI. Note that there is significant variation in potential ROI within cities, so most cities have neighborhoods within them with high temperature ROI.

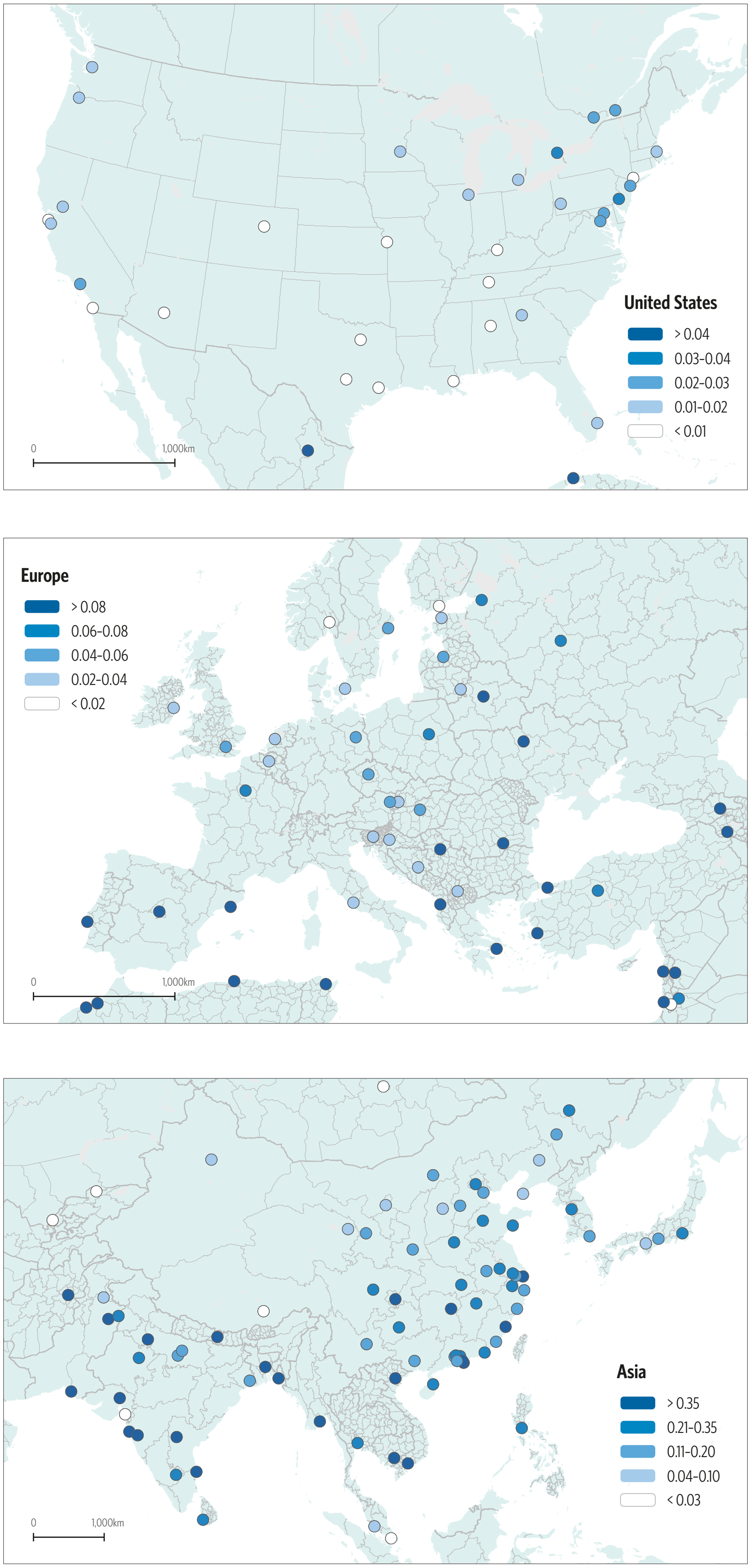
Photo © iStock, Blulz60

Again, maps of specific regions can also show interesting and important variation in median ROI for temperature mitigation (Map 12). Within North America (top panel), the high-density cities in the Northeast of the United States (New York and Philadelphia, in particular) and eastern Canada (Toronto and Montreal) have relatively high median ROI for temperature mitigation. There is also moderate potential for tree planting for temperature mitigation in cities in the western United States.

Within Europe (middle panel), there is a general trend for cities in eastern Europe having higher ROI for PM mitigation than cities in western Europe, driven primarily by the relatively high population density. Spanish cities look particularly promising, with a high media ROI for tree planting for temperature mitigation.

Within Asia (bottom panel), Indian cities have some of the highest ROI from tree planting for temperature mitigation, with cities in China having moderate ROI. Again, cities in Central Asia, by contrast, have lower population density and thus lower ROI.

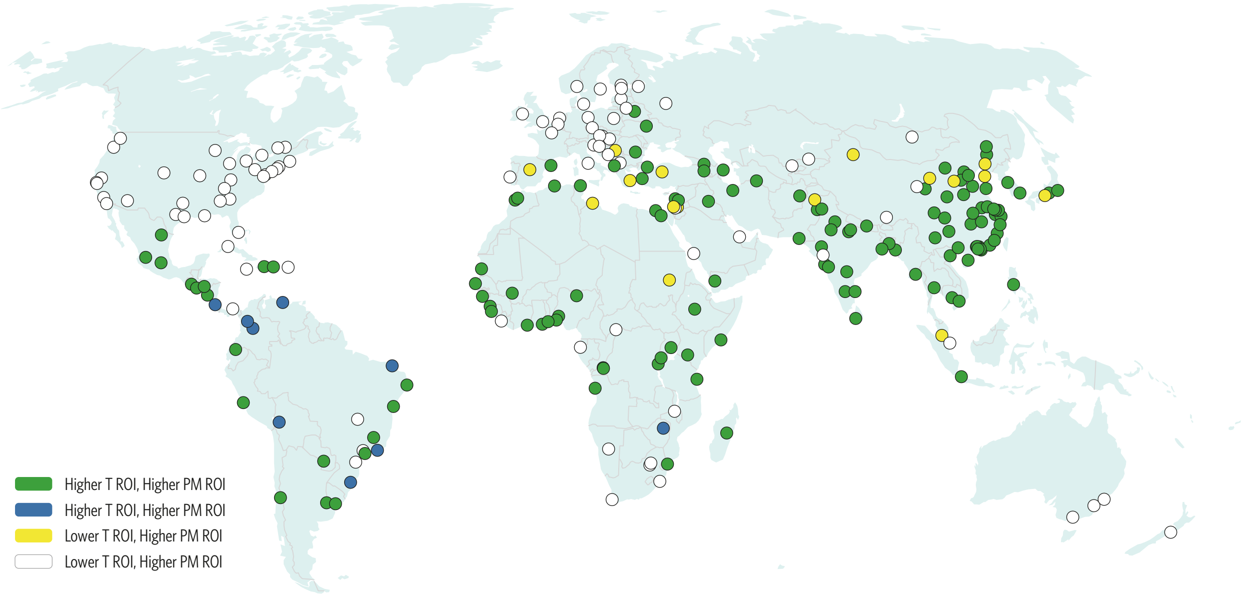
Temperature ROI (pop* reduction/$)



Map 12. Regional patterns of ROI of planting street trees to reduce temperature, expressed as median ROI.

Trees are a dual solution

Trees provide both particulate matter and temperature mitigation (as well as a host of other co-benefits). Map 13 shows the overlap of ROI for both particulate removal and temperature mitigation. Green cities have high ROI for both metrics, and are primarily located in south and east Asia, as well as west Africa, coastal South America, and Central America. These "win-win" cities are logical places for targeting tree-planting efforts at a global scale.



Map 13. Trees are a dual solution. Generally, cities that have higher ROI for PM reduction have higher reduction for temperature reduction (Green). The exception is cities in Latin America, where temperature ROI is higher but PM ROI is relatively lower (Blue), and a handful of cities in Asia, where PM ROI is higher but temperature ROI is relatively lower (Yellow).

Planting guidelines for healthy air

Cities have multiple goals when they plant trees. They want aesthetic beauty, but also want low-maintenance, disease-resistant trees that will be hardy in the local climate. There are also multiple different places cities plant trees, from crowded urban streets that are predominately pavement to more natural habitat and open space. Given this multitude of goals and places for trees, as well as the scope of this report, it is impossible to give specific recommendations about species selection or planting strategies. These specifics must be tuned to the needs of a local population. There are, however, some principles of tree planting for PM removal and temperature mitigation that can be incorporated into citys' planting plans.

Characteristics of tree species

Particulate matter mitigation—Tree leaves remove PM through dry deposition, and so tree species that have larger leaf surface area will generally remove more. A large total leaf surface area can occur because a species has a dense canopy, or because the leaf surface is "rough" (lots of ridges or hair), which increases the surface area for interception.[85] For instance, analysis of multiple tree species[86] found those that had more hair on their leaf surfaces, or more waxy surfaces, generally remove more PM. Another consideration is whether a tree is deciduous or evergreen. For the purposes of PM removal, being evergreen is a plus if PM removal is desired in the dormant (winter) season, when deciduous trees would be less effective. Yang and colleagues[85] provide a useful table, their Table 5, that lists the PM removal efficiency of the 100 most commonly used urban trees globally. Tree species that score high on PM removal efficiency include such common temperate species as eastern red cedar *(Juniperus virginiana L.)*, red maple *(Acer rubrum L.)*, American elm *(Ulmus americana L.)*, and white poplar *(Populus alba L.)*. Some common species that score poorly for PM removal include chokecherry *(Prunus virginiana L.)*, flowering dogwood *(Cornus florida L.)*, and white ash *(Fraxinus americana L.)*.

Temperature mitigation—Trees mitigate air temperature either by shading impervious surfaces (preventing heat storage) or by transpiring water (transferring energy to latent heat). Therefore, tree species that have a high leaf area index (defined as the ratio of leaf area to ground area under canopy) will cast denser shade and be more effective at reducing temperatures. In temperate areas with hot summers but cool winters, deciduous trees may be more appropriate. They will supply shade during the hot season but allow sun through in the cold season. Generally, the recommendation is that trees be selected that will be appropriate for a city's climate zone, including in terms of their water use, rather than specifically aiming to maximize water transpiration by trees (see Box on aridity and tree planting). Relatively few studies have looked at the temperature mitigation potential of specific species of trees, so for now cities looking to select species for temperature mitigation should select hardy, shade-providing trees appropriate to their climate. One interesting study in Addis Ababa[71] looked at the different temperature mitigation potential from different species, with eucalyptus *(Eucalyptus* spp.*)* cooling more than cypresses *(Cupressus* spp.*)*, Grevillea spp., and acacias *(Acacia* spp.*)*. On the other hand, a study in Mexico City[72] found that sweet gum *(Liquidambar styraciflua L.)* was significantly more effective at temperature mitigation than eucalyptus *(Eucalyptus* spp.*)*.

Types of plantings

Major roads—Major roads can be a significant source of air pollution from cars, including PM. Tree planting along such roads must be done with some care. Trees will reduce PM loading through dry deposition, but they can also inhibit air circulation, trapping pollution in and under the canopy. In some cases, this can be a good thing. For instance, a dense line of trees or shrubs can trap dirty air over the highway, preventing it from moving laterally into other parts of the city. However, if trees are trapping dirty air where people are moving or living this can result in accidentally increasing their exposure to particulate matter. ***Cities should be careful planting trees near major emission sources, considering the tree species to be planted, their eventual canopy volume, the geometry of nearby buildings and other features that block wind flow, and wind speed and direction***.[87] One study suggested that to be safe, along major roads single roadside tree lines should be planted of a tree species with high PM removal capacity, with enough spacing between tree canopies to allow wind flow between trees.[88]

Smaller roads—Many roads, however, are not major sources of air pollution, since they have relatively little traffic. These are, for instance, many of the residential streets on which urban residents live. Along these streets, there is less worry of trapping dirty air by blocking wind circulation. Maximizing tree cover to shade as much impervious area as possible will maximize the temperature reduction achieved. This greater leaf area will also allow more PM removal through dry deposition of any ambient PM that is floating in overall urban atmosphere. Since these street trees will be right next to homes and businesses, care must be taken that they are aesthetically pleasing, hardy enough to withstand an urban environment, and meet the other needs of those in cities.

Parks and other open space—Because the ability of trees to reduce PM and temperature is relatively localized (see Methods section for discussion), trees that are planted in the middle of urban green parcels (parks or other open space) have relatively less importance for making air healthier, simply because few people live or work within a few hundred meters of the tree. Thus, while the ability of particular tree species to reduce temperature or PM should be considered when selecting the list of species planted, it is likely that temperature or PM mitigation characteristics will be one of only a set of factors that are important to consider in a park setting (e.g., aesthetic beauty, wildlife value). In these settings, the value of parks and open space for recreation and socialization is likely one of the most important ecosystem services, so the ability of trees to reduce PM and temperature may be of secondary importance.

Chapter 4

Photo © Joanna B Pinneo

Nature Is a Cost-Effective Solution

Particulate matter mitigation

Our research also shows that planting trees can be a cost-effective way to reduce particulate matter. For particulate matter the cost of reduction, in $/ton, varies significantly across neighborhoods, and in some neighborhoods is lower than for other available grey infrastructure strategies (Figure 14). The median cost of tree planting for PM mitigation is $23,000/ton, which is higher than the median cost of 5 out of 6 broad categories of strategies we considered, suggesting that in many cases other grey infrastructure strategies may be less costly. However, in some neighborhoods, the cost of tree planting for PM mitigation is as low as $840/ton. So in some neighborhoods, tree planting appears to be the most cost-effective strategy.

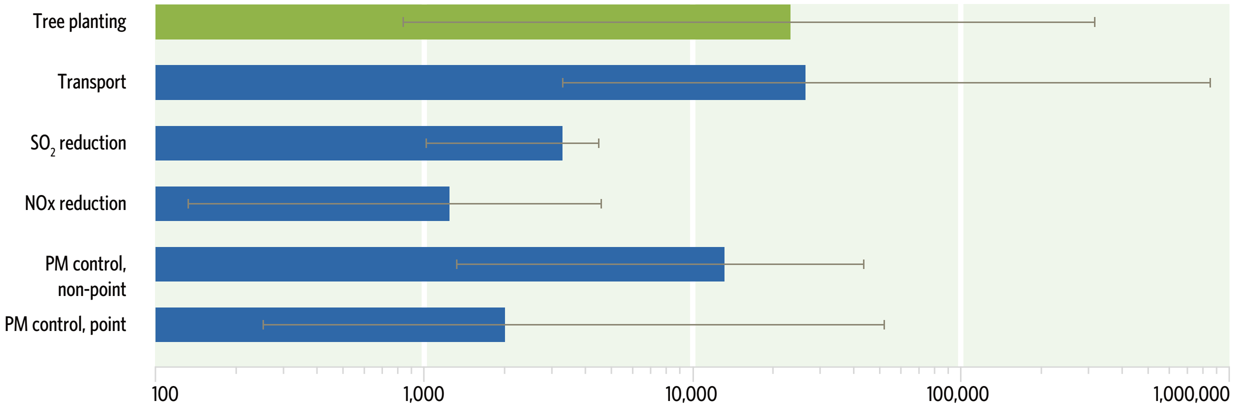


Figure 14. Cost-effectiveness of street tree planting to reduce particulate matter, compared with common categories of conventional mitigation strategies. The green bar shows the median cost-effectiveness of street tree planting across sites, while its error bars show the minimum and maximum cost-effectiveness. All values for cost-effectiveness are standardized to US2015$/ton. Both the costs and the tons removed are expressed as annual numbers. Note that while the median cost per ton PM removed is higher for street trees than the median cost of many conventional strategies, there is significant variance, and on many sites tree planting is cost-competitive relative to the other grey infrastructure strategies. Moreover, this comparison is biased in favor of conventional strategies because their cost-effectiveness is expressed in terms of $/t emissions avoided at the emissions source (not all of which translates into local concentration reductions for people), while that of trees represents the actual cost-effectiveness in producing local reductions for people.

Not only can nature be a cost-effective way to make air healthier, it can also deliver these benefits to a significant fraction of urban residents. The global investment curve for trees to reduce $PM_{2.5}$ pollution is shown in Figure 15. For instance, an annual $100 million additional global investment in trees (including planting and maintenance costs) would give 8 million additional people a reduction of > 10 $\mu g/m^3$ in $PM_{2.5}$, 47 million people a reduction of > 5 $\mu g/m^3$, and 68 million people a reduction of 1 $\mu g/m^3$ (Medium impact scenario). The maximum possible tree planting we considered would involve spending an additional $3.2 billion annually in our study cities, which works out to about $17 annually per person benefited. In return, we estimate this maximal tree-planting scenario would give 9 million additional people a reduction of > 10 $\mu g/m^3$ in $PM_{2.5}$, 59 million people a reduction of > 5 $\mu g/m^3$, and 182 million people a reduction of > 1 $\mu g/m^3$ (Medium impact scenario).

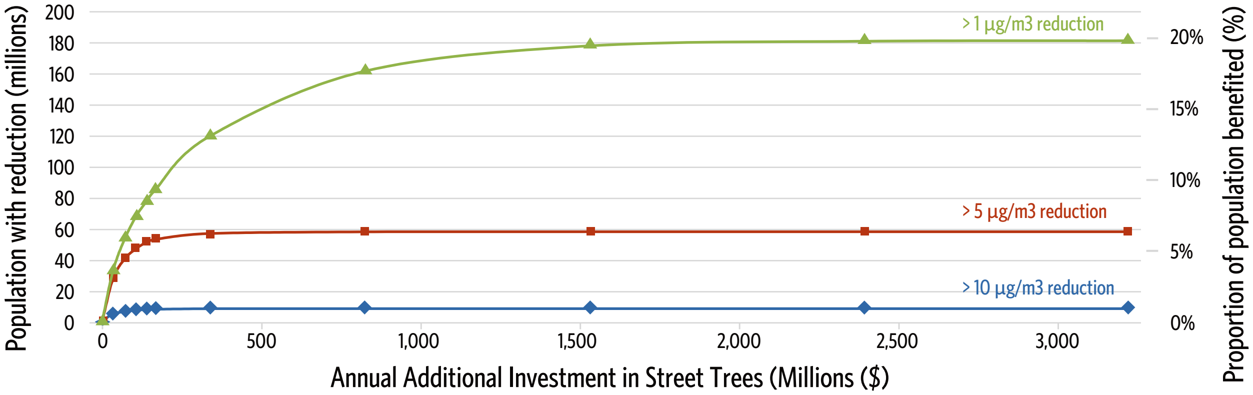


Figure 15. The global potential for street trees to benefit urban dwellers with reduced PM concentrations, given different annual investments in tree planting and maintenance. Results shown are for our Medium scenario of the effectiveness of trees in removing PM. Note that the curves for 5 and 10 µg/m^3 flatten out at high investment levels because there are relatively few cities (principally the most polluted) where street tree planting can remove more than this amount of pollution. Once investment in street tree planting has fully occurred in these cities, additional investment in tree planting won't increase the number of people receiving a reduction of more than 5 µg/m^3, but will continue to increase the number of people receiving more modest reductions of 1 µg/m^3.

These magnitudes of reductions in PM$_{2.5}$ concentrations and temperature achievable with tree cover can provide modest but significant reductions in disease. In this report, we focus only on mortality numbers, primarily because there is a large and robust literature relating ambient PM concentrations to mortality. However, note that there are, of course, a range of health impacts, from missed days at school or work to hospitalizations to premature death. Indeed, for every person killed by ambient PM, there are perhaps dozens who have their lives negatively impacted in other ways. Moreover, trees can play a role in mitigating pollutants other than PM (e.g., ozone), which are not considered in this analysis, so our estimates must be considered conservative lower estimates.

There are a number of papers that estimate a functional relationship between ambient PM concentrations and mortality rate.[89, 90] For our calculations, we follow the recommendations of the World Health Organization.[91] We estimate that the maximum possible tree planting in our cities would reduce PM-related mortality by 2.7 percent to 8.7 percent, saving between 11,000 and 36,000 lives annually in our study cities. Since this maximum tree-planting scenario cost $3.2 billion annually, that works out to a cost of $90,000 to $290,000 per life saved. While the statistical value of a life is a complex and controversial topic, and a full discussion is beyond the scope of this report, we would note that for most countries the statistical value of a life far exceeds this value. For instance, in the United States, the Environmental Protection Agency has set the value of a statistical life at $9.1 million for the purposes of evaluating restrictions on air pollution.[92]

Temperature mitigation

Planting trees is also a cost-effective strategy to reduce air temperatures (Figure 16). The cost of reducing temperatures (in $/° C from implementing the practice over a 100-square-meter area) varies significantly across neighborhoods, and in some places is lower than for any available grey strategy. The median cost of tree planting ($468/° C) is less than every other strategy considered except for cool-roof technologies. Note also that one advantage of tree planting is that it cools the air along sidewalks and other places people move. Cool-roof technologies, by contrast, decrease ambient air temperatures in the column of air above the roof, where few people will experience the lowered temperature.[67, 93] Cool-roof technologies, however, can significantly reduce the amount of energy needed for cooling a building during summer (see Box 3 for discussion of air temperature and electricity use).

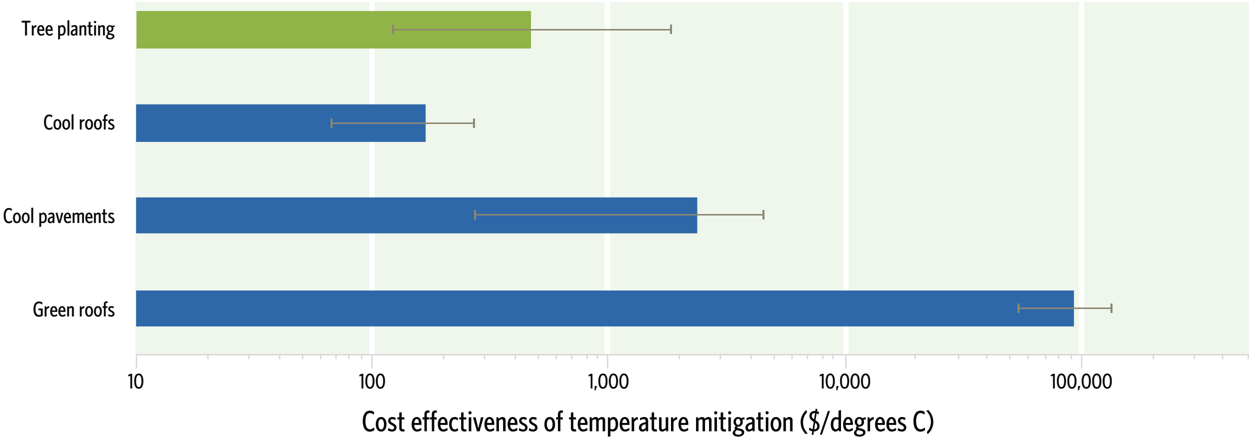


Figure 16. Cost-effectiveness of tree planting to reduce temperatures, compared with alternative strategies to reduce air temperature. Cost-effectiveness is expressed as the cost to build a 100-square-meter installation, divided by the annual reduction in temperature. The green bar shows the median cost-effectiveness of a 100-square-meter tree planting across sites, while its error bars show the minimum and maximum cost-effectiveness. In this calculation, we are assuming a 20-year lifetime for installations. For cool roofs and cool pavements, we are accounting for only the incremental additional cost of the cool technology, above and beyond standard construction practices. Data taken from the EPA's Reducing Urban Heat Islands: Compendium of Strategies, which discusses in more detail specific technologies within each of these broad categories.

Tree planting also has enough scope to help lots of people The global investment curve for trees to reduce temperature is shown in Figure 17. An annual investment of $100 million would give 77 million people a 1° C (1.8° F) reduction in maximum temperatures on hot days (Medium scenario). The maximum possible tree-planting scenario (an additional $3.2 billion annually in our study cities) would provide 220 million people with a 1° C (1.8° F) reduction in maximum temperatures on hot days (Medium scenario), which works out to about $15 per person annually benefited.

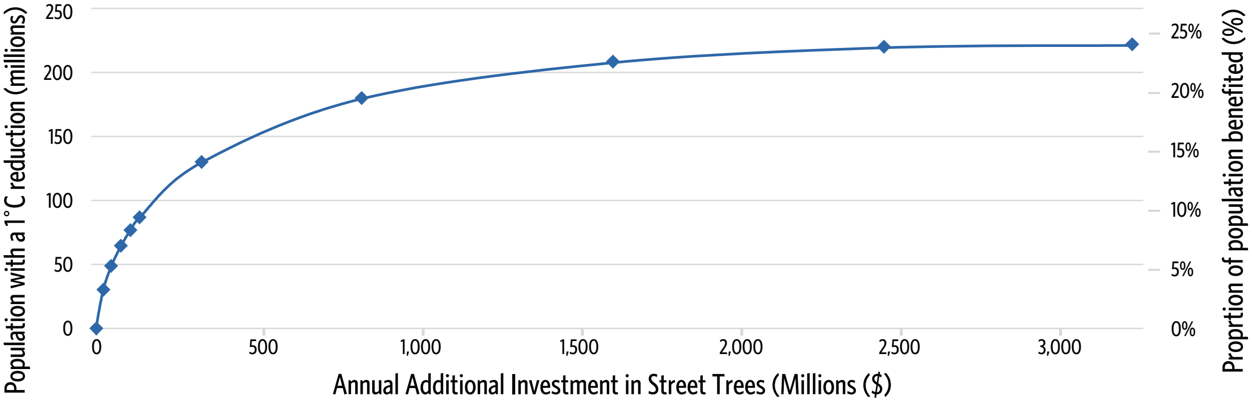


Figure 17. The global potential for street trees to benefit urban dwellers with reduced temperatures, given different annual investments in tree planting and maintenance. Results shown are for the Medium scenario. Under the High scenario, an equivalent number of people would see a 2°C reduction, whereas under the Low scenario, the same number of people would see a 0.5°C reduction.

The effect of high temperature on mortality is well documented, with a few studies estimating the regression relationship between temperature and mortality.[14, 20] Most functional forms look at the mortality increase when ambient temperature increases above a certain threshold temperature. For this report, we use the relatively simple methodology used by McMichael and colleagues,[14] which uses a linear relationship between mortality and temperature above a safe threshold. We estimate that the maximum possible tree planting in our cities would reduce high temperature-related mortality by 2.4 percent to 5.6 percent, saving between 200 and 700 lives annually in our study cities. Again, remember that for every death due to high temperatures, there a dozens of people who suffer some sort of medical problem because of the high temperatures. And, of course, in our maximum tree-planting scenario there are 220 million people who would have a more pleasant experience outside every summer.

Box 5: Street trees, electricity use, and climate change

Another co-benefit of street trees is that they can help mitigate climate change, either through directly sequestering carbon itself or (more importantly) by reducing electricity use for cooling and hence greenhouse gas emissions. The effect of trees on electricity use for cooling operates in two main ways: Shade from trees reduces the direct solar heating of homes, reducing the need for air conditioning; and trees can reduce ambient air temperatures, which thus lessens the need for cooling of the air inside homes.[94] One set of studies has modeled and measured the benefits that trees can provide, primarily to residential single-family homes. For instance, McPherson and Rowntree[95] report a 2 percent to 9 percent reduction in annual heating and cooling costs from a single, well-placed tree. Another set of studies has looked at the empirical relationship between ambient temperature and electricity use. A recent review by Santamouris and colleagues[96] found that each increase in temperature of 1˚C (1.8 ˚F) caused an increase in monthly residential electricity use from 4 percent to 8.5 percent.

A number of factors affect the magnitude of this reduction in residential electricity use and hence the avoided greenhouse gas emissions:

- Orientation: Trees on the sunnier side of a house (e.g., the south side of a house in the Northern Hemisphere) cause a greater reduction.
- Distance to house: Trees closer to the house have more of an impact.
- Size and density of canopy: Canopies that cast more shade cause a greater reduction.
- Size and construction of building: More of the published research showing benefits is for one- or two-story houses, with trees appearing to have less of an effect on the electricity use of larger buildings.
- Type of energy used: Obviously, the greenhouse gas implications of a reduction in electricity depend greatly on the carbon intensity of electricity production. Electricity produced from coal, for instance, causes more life-cycle greenhouse gases than electricity from hydropower.

It is beyond the scope of this report to fully account for all these factors. Nevertheless, we wanted to construct a rough estimate of how the kind of street tree planting considered in this study would impact electricity use and greenhouse gas emissions. We base our estimate on the range of effects shown by Santamouris and colleagues.[96] Note that our analysis only considers street trees (not trees in individual parcel's yards, etc.), and we only consider the potential energy savings to residential electricity consumption for cooling. Furthermore, our assumptions about plausible planting targets (see discussion above, and in the Methods section) mean that at most only a fraction of homes benefit from an electricity reduction. It is not plausible for all homes in a neighborhood to be helped by additional street tree planting.

Based on statistics of per-capita residential electricity consumption from the U.S. Energy Information Agency's International Energy Outlook,[97] we estimate the total residential electrical energy use of our 245 study cities as 1,000 billion KWh. For context, this is less than 1 percent of the total global final energy consumption of all types of energy (electricity, fossil fuels for heat, liquid fuels for transportation, etc.). We estimate that our maximum possible street tree -planting scenario (an additional $3.2 billion annually in our study cities) would reduce residential electrical use by 0.9 percent to 4.8 percent annually (9.3 billion to 48 billion KWhr). This works out to a cost of $0.07 to $0.34 per KWHr saved.

Using statistics from the International Energy Agency on the carbon intensity of electricity production,[96] we estimate the total emissions of CO_2 from our 245 cities as 480 million tons. For context, global CO_2 emissions are around 40,000 million tons CO_2. Under the maximum possible street tree-planting scenario, the total emissions of CO_2 from our 245 cities are reduced by 0.9 percent to 4.6 percent (4.3 million to 22 million tons CO_2).

Photo: ©TebNad

Trees, of course, also directly sequester carbon as they grow. Several studies have tried to measure the net carbon sequestration of urban trees, accounting for both their carbon stored over time as the trees grow, as well as the carbon involved in the planting and maintenance of the trees. Nowak and colleagues estimated net sequestration for a set of U.S. cities, finding an annual rate ranging from 0.081 (kgC per square meter of tree canopy) in Minneapolis to 0.401 in Omaha.[98] If we apply these rates to our maximum street tree planting scenario, we can make a rough estimate that the maximum planting scenario (an additional $3.2 billion annually in our study cities) would increase net carbon sequestration in our 245 cities by 2.7 million to 13 million tons CO_2. Combining with our estimates of avoided CO_2 emissions from electricity reduction, we can estimate the total impact of our maximum street tree-planting scenario as an annual reduction of 7.0 million to 35 million tons CO_2. This works out to a cost of $90 to 450 per ton of CO_2 avoided.

Note that this is a relatively high cost, compared to other ways to mitigate greenhouse gas emissions. Remember, though, that we were only considering street tree planting and maintenance costs, which are substantially more than forestry in a rural setting. Also, residential electricity use for cooling is relatively modest outside of the most economically developed countries currently, which limits the potential for tree planting to reduce residential electricity use in developing countries. This may change as the developing world increases its use of air conditioning. Regardless, keep in mind that the climate change mitigation benefits are just one of several co-benefits trees provide. *In particular, all of these climate mitigate benefits are provided in addition to the benefits to human health from PM reduction and temperature mitigation.*

Adding up multiple benefits

Of course, in cases where both PM concentrations and high temperatures are a concern, the comparative attractiveness of tree cover additions would be much higher still, as none of the grey alternatives address both heat and PM problems. Moreover, the other co-benefits that trees provide (carbon sequestration, aesthetic beauty, stormwater mitigation, healthier and more walkable communities, etc.) further increase the comparative attractiveness of tree cover. As discussed above, there are tools (e.g., i-Tree) that allow a first-order estimation of the total value of a street tree. In general, we expect based upon the literature that in many cities, the economic value of these other co-benefits will exceed the value of heat and PM mitigation.

One example may illustrate this. One study showed larger street trees increase the value of nearby residential homes by 3 percent in Portland, Oregon.[99] The median home price in Portland is around $350,000, so street trees fronting a typical home are associated with an increase of around $10,000. In absolute terms, this is likely much greater than the absolute value these street trees provide in terms of PM or temperature mitigation to people in Portland.

We recommend that cities try to consider the broad spectrum of benefits trees provide when they are evaluating the return on investment of their planting, rather than focusing solely on their value for PM and heat mitigation.

Chapter 5

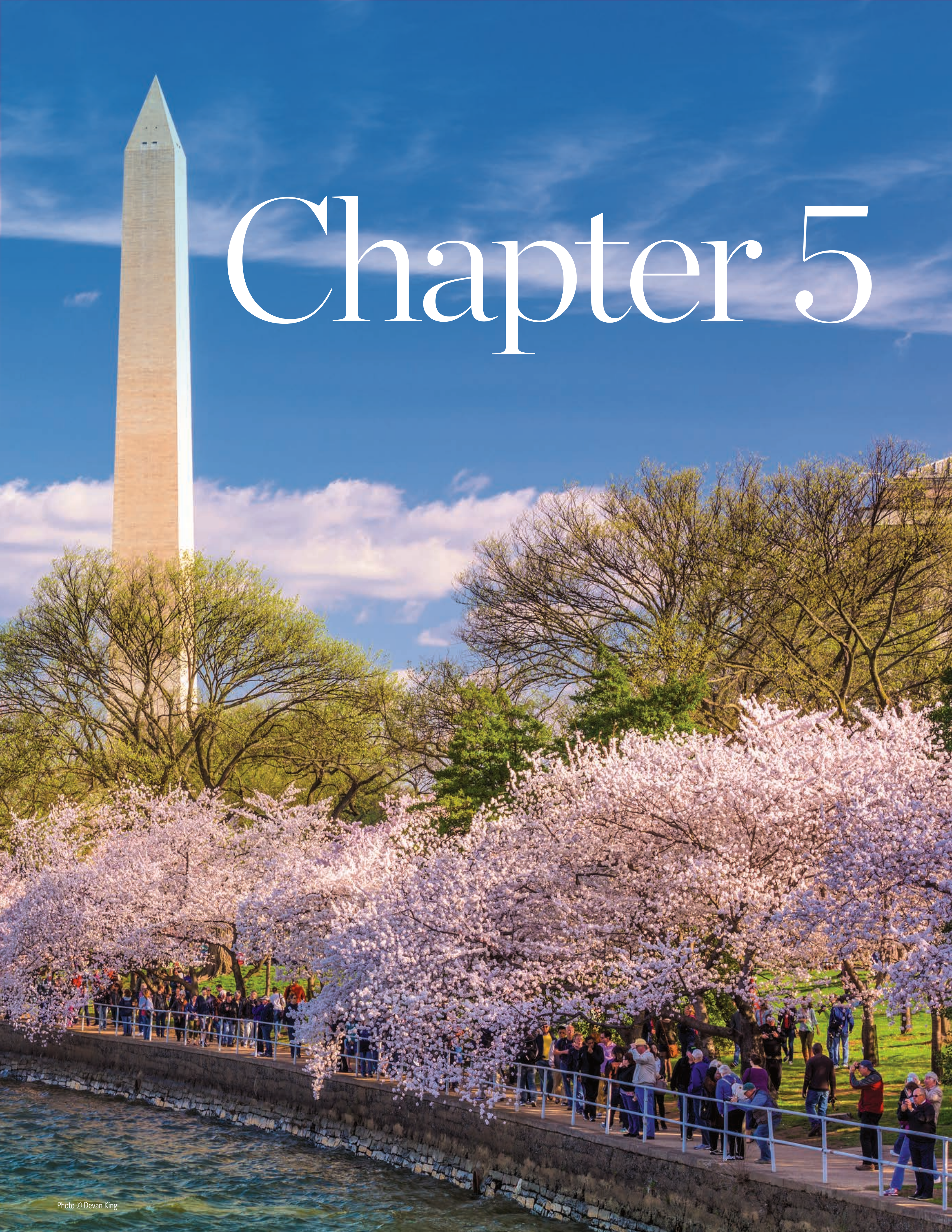


Photo © Devan King

Nature Will Matter Even More in the Future

Finally, our analysis of trends over time suggests that the ecosystem services supplied by trees will be even more crucial in the future. This is for three main reasons:

1. **More demand for the services trees provide:** There may be a 50 percent increase in the rate of mortality caused by $PM_{2.5}$ by 2050, most of it in urban areas [11], and summer maximum temperatures in our sample of cities are forecast to increase by 2 to 5˚C (4 to 9° F) over the same time period. While these twin threats post a challenge to the health of those in cities, all else being equal, they will also increase the importance of the trees that are already there.
2. **More people:** There will also be a dramatic increase in urban population (Figure 18.), which increases the number of people who might benefit from nature's services. Urban population will increase from 4.0 billion to more than 6.3 billion in 2050, an increase of more than 50 percent. Some of this urban population increase will be to new neighborhoods, developing on green field sites on the fringes of existing urban areas. But some fraction of this urban growth will be in existing urban areas, increasing urban population density. Any increase in urban population density increases the ROI of tree planting.
3. **Potentially fewer trees:** Finally, all this urban development, or simply societal underinvestment in replacing trees lost, may reduce the amount of urban greening. For instance, we found that 26 percent of cities had a decline in forest cover over the period from 2000 to 2010, whereas only 16 percent of cities had an increase in forest cover over the time period. If this trend continues, there will be fewer trees in cities precisely when there is more of us in cities, who need the services trees can provide.

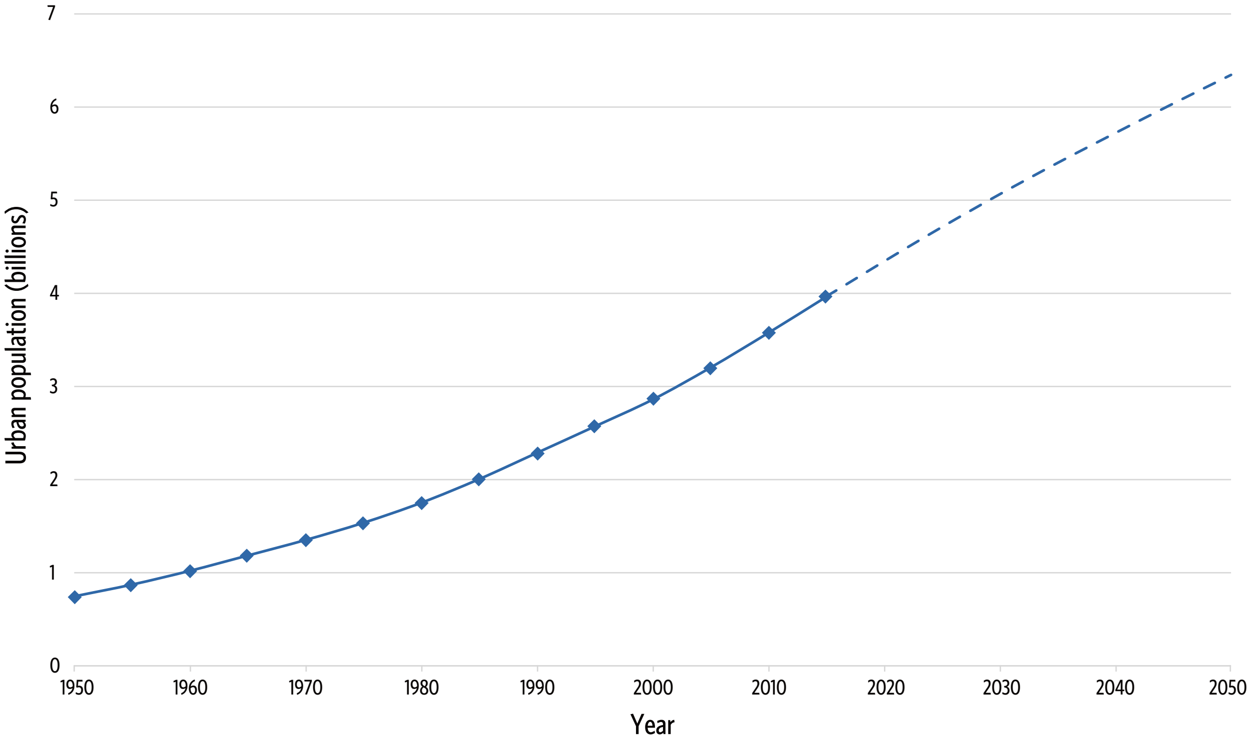


Figure 18. Global urban population growth from 1950 to 2015, and then forecasted out to 2050. Data are from the UNPD's World Urbanization Prospects database.

Trees

can actually take pollution out of the air—reducing fine particles in their immediate vicinity by as much as a quarter.

Case Studies

How cities are striving to make their air healthier

Photo © Chris McGuire / Radius Images

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ATLANTA

Atlanta lacks the dramatic geographical features of many of the world's major cities—a harbor, a river or lake, a view of distant, snow-capped mountains. What it has in abundance, as becomes clear on any flight into the teeming chaos of Hartsfield-Jackson airport south of town, are trees—magnolia, pecan, sweetgum, elm, oak, poplar, beech, and dozens of other species. The trees form a dense canopy over parts of the city and have earned Atlanta the nickname "the city in a forest."

Trees define Atlanta. The main thoroughfare is called Peachtree Street. The Dogwood Festival has been running for 80 years and draws more than 200,000 people to Piedmont Park every April. The tree canopy itself covers almost half of the 133 square miles that constitute Atlanta proper, according to a 2014 assessment by the Atlanta Tree Conservation Commission and Georgia Tech, making it the most heavily forested city in the country.

Older parts of Atlanta were spared the rampant timbering that cleared much of Georgia in the late 1800s. Some trees even survived the blaze that consumed the city in 1864—a tulip poplar known as "Grandfather" has stood in Brookhaven, north of downtown, since before the Revolutionary War.

Atlanta has stringent ordinances aimed at protecting its trees. The city charges up to $1,000 to cut down a single one as small as six inches in diameter. The law regulates tree removal on private property, which reflects the reality that more than three-quarters of the city's tree canopy exists in residential areas outside of the city core, while parks and public green-space occupy only 6 percent of city land.

Yet Atlanta's trees are far from safe, despite the ordinances and the city's commitment to staying green. That troubling news threatens to compound a problem Atlanta's residents know all too well: The heat.

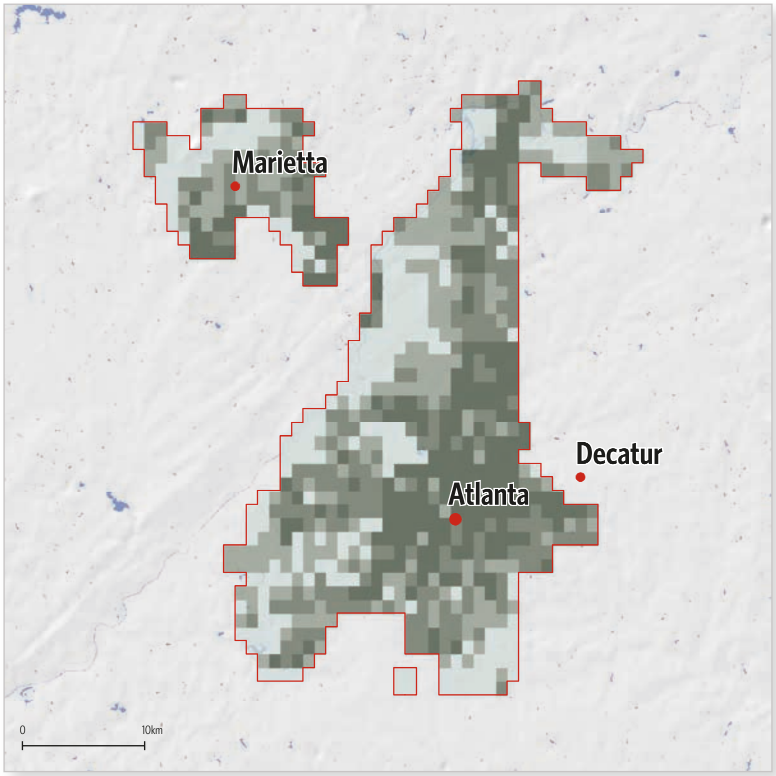
In March 2016, Atlanta hit 29° C (84° F), a record for the month. Within the next 50 or 60 years, Atlantans could see as many as 50 days each year with temperature exceeding 35° C (95° F). The problem is not just changes in climate, but also changes in where people want to live, with the fastest growth in the south and west. According to a recent study, by the middle of the century, four to six times as many Americans will endure 35-degree days than at the end of the last century. Researchers found that people living in Atlanta, along with those in Charlotte, Dallas, Houston, Oklahoma City, Phoenix, Tampa, and San Antonio, are most at risk of enduring many more 35-degree days by 2050.

Atlanta's tree canopy can help mitigate some of the problem, but only if it remains more or less intact. The biggest current threat to Atlanta's trees, ironically, comes in response to the previous threat. For decades, greater Atlanta has been a prime example of the pitfalls of suburban and exurban sprawl. Metro Atlanta's urbanized land base grew 72 percent between 1982 and 1997, while its population grew 58 percent. More than 600,000 acres were converted to urban uses in Atlanta between 1982 and 1997—200,000 more than Los Angeles, even though L.A. grew by nearly three times as many residents. The trend has continued: Between 2001 and 2006, one metro county, Gwinnett County, alone lost more than 3,000 forest acres per year, and canopy cover dropped from 52 percent of the county in 1991 to 37 percent by 2005.

Population projections suggest that sprawl may be slowing, but growth is not. According to the Urban Institute, Atlanta's population could grow by as much as 59 percent by 2030, bringing its total population to more than 7.5 million. Other projections suggest the population could top 10 million by 2060—only Phoenix, Arizona, and Riverside, California, are projected to grow faster. And growth within Atlanta's urban core poses a threat to the city's trees. Population growth within the city and a surge in denser development represents a welcome shift from car-centric sprawl, but those trends are paired with infill development that puts older, canopy trees at risk.

Fortunately, groups like Trees Atlanta, a nationally recognized NGO, and others are working to find ways to balance development with the need to preserve the city's trees. As the results of this study show, Atlanta neighborhoods could benefit from reduced temperatures from street tree planting. While at a city-level the ROI of tree planting is relatively low, compared with other cities globally, there are neighborhoods with relatively high ROI in tree planting in high-density neighborhoods that run north-south, roughly following the Interstate 85 corridor. An increased annual investment of $3.1 million might give more than 80,000 people a 1.5° C (2.7° F) reduction in temperature.

Results from the Atlanta study



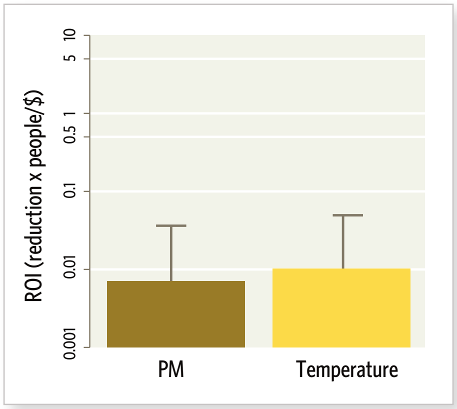


Figure 19. ROI for tree planting for Atlanta.

PM ROI

▇ ▇ ▇ ▇

Higher Return Lower Return

Map 14. Neighborhood-level ROI for Atlanta (temperature reduction).

Investment	Annual Cost ($)	> 1 ug/m^2 PM$_{2.5}$	1.5 deg C
10% of sites	3,140,000	29,300	81,200
20% of sites	5,200,000	39,500	113,000
Full Investment	17,800,000	64,200	187,000

Table 7. Temperature and PM reduction benefits under three investment scenarios for Atlanta.

BEIJING

Photo © iStock, ispyfriend

In late 2014, Beijing hosted an important regional meeting: the Asia-Pacific Economic Cooperation (APEC) summit. Heads of state from 21 countries attended. China's leaders saw the gathering as an opportunity to showcase its progress and economic vitality.

One area of progress was apparent: China has made impressive strides in recent years in cutting coal emissions, switching to natural gas for electricity generation and replacing coal-fired builders with electric heating systems in the city center. In outlying areas, the government has encouraged residents to switch from cheap, untreated smoky coal to smokeless coal—though many continue to use the dirtier version.

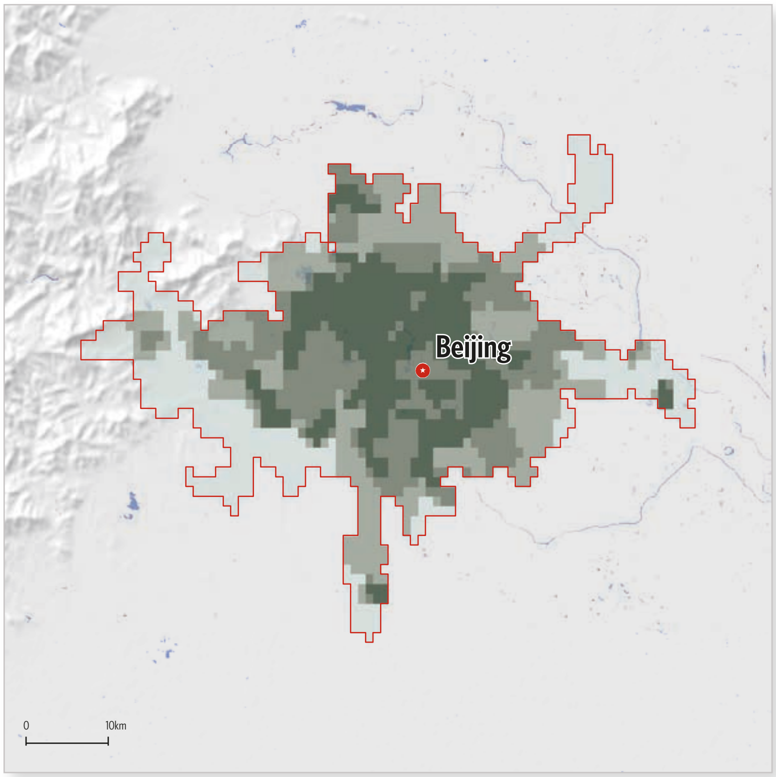
Still, like most megacities around the world, Beijing faces air-quality challenges. On the worst days, visibility drops to a few hundred yards. The problems can worsen during cold winters, when households, particularly on the outskirts of the city, burn more coal for heat.

Beijing's pollution problem is hardly a secret. In March, 2014, more than six months before the APEC summit, Premier Li Keqiang promised to "declare war" on pollution and fight it with an "iron fist."

The government's efforts have had some success. Beijing has more days when skies clear and the mountains are visible in the distance. Longer lasting solutions, however, will require more fundamental changes. Planting trees can be a part of that effort. Overall, the city has a high ROI of tree planting, relative to other cities. The central neighborhoods of the city have the highest ROI for PM reduction. We estimate that for an annual additional investment of \$2.9 million in street tree planting, 2.2 million people could have a greater than 1 $\mu g/m^3$ reduction in $PM_{2.5}$. Note that for many people in Beijing, reduction would be much greater, exceeding 10 $\mu g/m^3$ for most people near trees.

Planting trees can play a role in clearing Beijing's air, but it will not suffice. Beijing is now well into a five-year effort to cut coal burning by more than half, restrict the number of cars on the road, introduce a pilot cap-and-trade program, and urge factories to disclose their emissions publicly. The city has shut down manufacturing firms for polluting and taken thousands of inefficient vehicles off the roads. The city hopes to reduce $PM_{2.5}$ concentrations by 25 percent by 2017.

Results from the Beijing study



PM ROI

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Higher Return Lower Return

Map 15. Neighborhood-level ROI for Beijing (PM reduction)

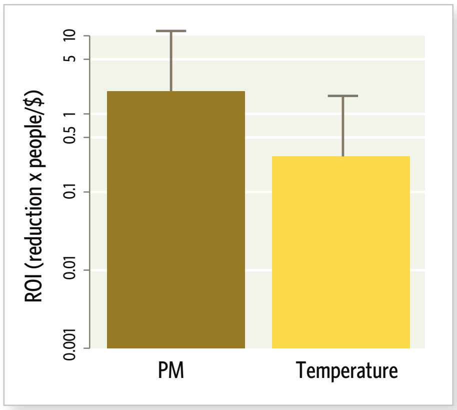


Figure 20. ROI for tree planting for Beijing.

Investment	Annual Cost ($)	> 1 ug/m² $PM_{2.5}$*	1.5 deg C
10% of sites	2,940,000	2,220,000	2,230,000
20% of sites	5,890,000	3,600,000	3,610,000
Full Investment	29,400,000	7,510,000	7,510,000

*Note: Most people will receive a reduction of > 10 ug/m² $PM_{2.5}$ in this city.

Table 8. Temperature and PM reduction benefits under three investment scenarios for Beijing.


Photo © iStock, knowlesgallery

DENVER

In the 1970s and 1980s, Denver's air pollution was so bad it made national news. The bad air even had a name: the brown cloud. In 1989, after the Denver Broncos had lost their third Super Bowl in as many appearances, a CBS sportscaster joked that Denver had ''never been No. 1 in anything—but carbon monoxide.''

The joke stung because it was largely true. In 1975, Denver violated Federal carbon monoxide standards 177 times.

The stain on both the city's air and its reputation, not to mention the health of its residents and its tourist industry, prompted a lengthy and aggressive campaign to fight pollution. Denver banned construction of new wood-burning fireplaces and the use of old wood-burning fireplaces on pollution ''alert'' days, which dramatically cut the amount of wood smoke in the air. The city began using more liquid de-icers on roads following snowstorms, replacing the sand that would get ground into fine particles and end up in the air as part of the brown cloud.

The problem is one of location as well. Denver sits in the South Platte river basin, bounded to the west by 13,000-foot peaks, a perfect recipe for smog. The wind often does not clear the air, and the high altitude means older cars burn gasoline less efficiently because the air has less oxygen. In response, Colorado enacted the nation's first oxygenated fuels program in 1988. Two years later, 39 cities across the country were required to use oxygenated fuel under the Clean Air Act.

In 2007, Denver's Mayor (now Colorado Governor) John Hickenlooper launched an ambitious effort to make the city sustainable by 2020. Among the initiatives was Greenprint Denver, a city agency that plans and coordinates citywide environmental programs. According to the Green City Index, a research effort sponsored by Siemens, Denver is now a model of environmental governance and is the fifth-greenest city in the United States and Canada, falling behind only San Francisco, Vancouver, New York City, and Seattle. Denver now has some of the strongest clean air policies in the United States, according to the report.

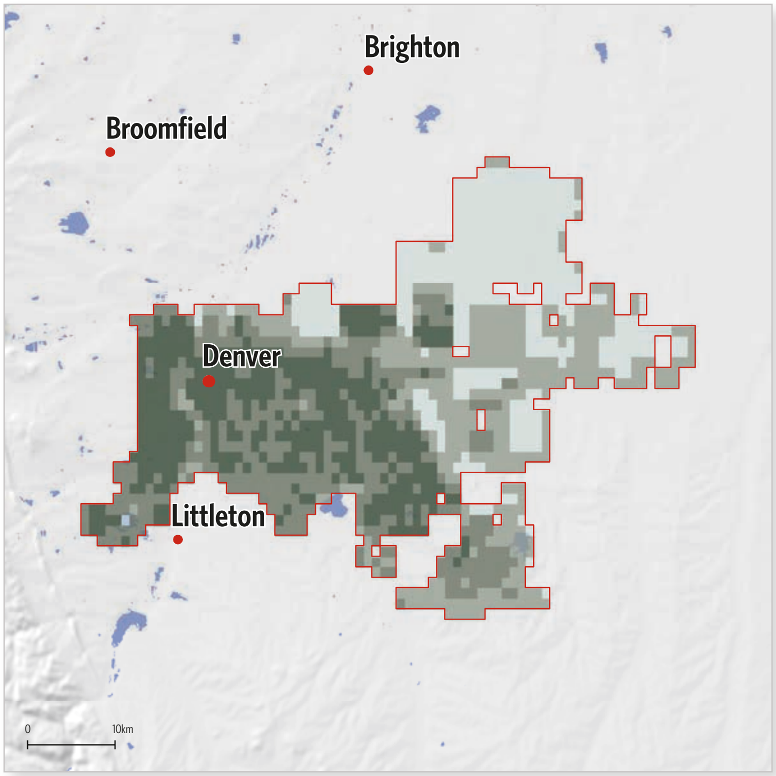
Population growth is part of the continuing challenges to Denver's air quality. In 2014, Denver reached number 6 on the *Forbes Magazine* list of the 20 fastest-growing cities in the country. The city's population now tops 3 million and is expected to continue to grow. The expanding population also means more cars, and even though each new car is far cleaner than in past years, the sheer number of vehicles on the roads means an increase in pollution.

Denver is continuing its efforts to be more energy efficient, reduce its deep dependence on coal, and make new building greener. Not all of Denver's sustainability projects, however, have worked out as planned. The Mile High Million, an effort to plant a million trees in the city by 2025, was canceled because of budget cuts in 2013, having gotten less than halfway to its goal.

Compared to some cities, Denver has a relatively low median ROI of tree planting, since the population density of its neighborhoods is relatively low. However, some neighborhoods in Denver (the denser neighborhoods near the historic downtown) have relatively high ROI of tree planting. Note that since Denver's PM concentrations are relatively low already, by global standards, the absolute reduction in PM that trees could provide is likely below 1 μg/m^3.

Among the most promising of Denver's efforts to become a greener city focus on rehabilitating old industrial sites. Denver's Brownfield Program is looking for ways to revitalize 3,500 acres of land along an 11-mile portion of the South Platte, an area that contains 33 brownfield sites. Green space along the South Platte could eventually help connect two recent additions to the National Wildlife Refuge system, both of which were brownfields of a different sort: the 25-square-mile Rocky Mountain Arsenal northeast of the city, and Rocky Flats, a far smaller Cold War-era nuclear weapons trigger factory to the west.

Results from the Denver study



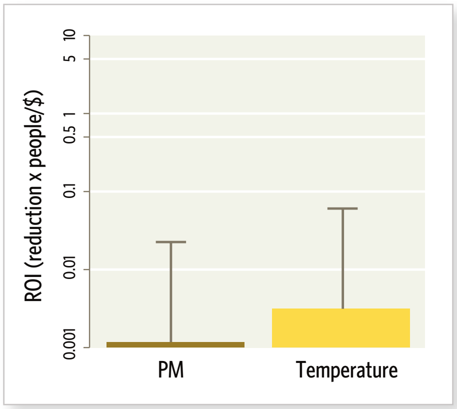


Figure 21. ROI for tree planting for Denver.

PM ROI

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Higher Return · Lower Return

Map 16. Neighborhood-level ROI for Denver (PM reduction).

Investment	**Annual Cost ($)**	**> 1 ug/m^2 PM$_{2.5}$**	**1.5 deg C**
10% of sites	3,500,000	0	110,000
20% of sites	6,980,000	0	185,000
Full Investment	26,200,000	0	301,000

Table 9. Temperature and PM reduction benefits under three investment scenarios for Denver.

HONG KONG

Photo © iStock, Andrea Izzotti

Few cities provide a more ideal setting to study the phenomenon of the urban heat island than Hong Kong. First of all, it is one of the most densely populated places on Earth, and also one of the richest. So Hong Kong's towering skyscrapers and extensive road network offer a true test of how modern urban development will shape local climates.

Second, and just as important, Hong Kong has historical climate data dating back more than 130 years, thanks to the Hong Kong Observatory. Nearly continuous temperature records have been kept since 1884 (save for during World War II), and several analyses of those records attribute much of the roughly 2° C (3.6° F) increase in average temperature to the heat generated through infrastructure development.

The trend is continuing, and may be accelerating. Indeed, a 2007 study by scientists at the Observatory predicted that by 2100, there will be less than one cold day a year (12° C or below), meaning that for some winters, there will not be any cold days at all, and winter could disappear in Hong Kong.

The island's location and topography play a role in how development is shaping the climate. Located at the entrance of the Pearl River Delta, Hong Kong is humid and subtropical. Its steep hillsides concentrate development onto the relatively few areas flat enough for high-rise buildings.

The tall, densely packed buildings are stifling street-level airflow, according to Observatory data.

Average wind speeds at a weather station on the mainland portion of Hong Kong (the area once called Kowloon) dropped from 3.5 meters per second in 1968 to two meters per second in 2014. The urban calm contrasts with the Observatory's remote Waglan Island weather station, southeast of the city, where wind speeds have been stable over the last 50 years.

The stagnant air is unable to disperse heat and pollutants, warns Professor Li Yuguo, who heads the mechanical engineering department at the University of Hong Kong. The combination of warmer air and lower winds is leading to what Li calls an "urban dome." His team found that, in the absence of winds, convective heat from individual buildings rose and formed a dome-shaped accumulation of warm air and pollutants above the city.

Some urban redesign may help alleviate the problem. Li, for example, suggests keeping secondary streets along northern Hong Kong Island wide and short to facilitate downslope windflow from the hills. Another option would be to keep the ground floors of tall buildings open, to promote air circulation at street level, though this would mean foregoing the valuable commercial real estate that now occupies much of downtown Hong Kong.

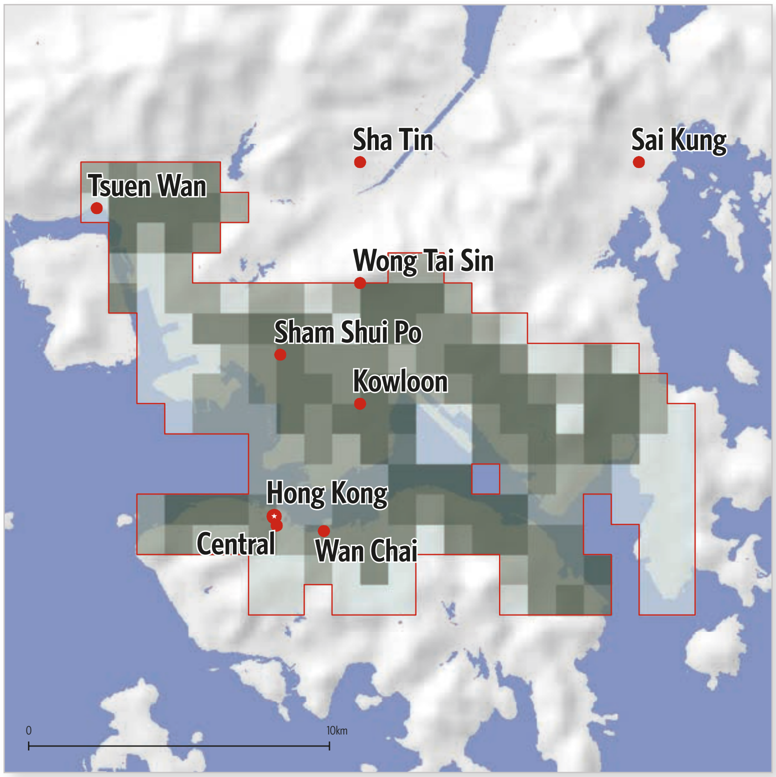
Government incentives could help prompt developers to provide better ventilation and make land pricing policies more flexible. They could also promote better use of Hong Kong's waterfront. In New York, another densely populated island city, all the streets run toward water and bring in cooler air. But Hong Kong's main thoroughfares run parallel to Victoria Harbor, so tall building close off the sea breeze from one direction, while the steep hills close off the other.

The news is not all bad for Hong Kong. Despite the dense population and the growing demand for buildable land, the city still boasts ample green space. Just 7 percent of Hong Kong is zoned for residential use. Parks, hiking trails, and beaches ring the city. Hong Kong's country parks cover about 40 percent of the territory's roughly 1,108 square kilometers of land.

While the parks are off-limits to development, at least for now, other green spaces may be more vulnerable. Hong Kong has set aside other greenbelt areas to act as a buffer against urban sprawl, but with land values skyrocketing the pressure to expand into those areas is intense. In 2015, the city's Development Bureau said the greenbelt areas were "suitable for urban expansion and thus have good potential to be rezoned for housing purposes."

As a high-density city, Hong Kong has a relatively high ROI of tree planting. Hong Kong is a fairly compact city, so the minimum mapping unit of our analysis (1 square kilometer) gives us relatively little detail into which neighborhoods in Hong Kong have the highest ROI. The compact size of Hong Kong also means that a small additional investment in street tree planting could have significant benefits.

Results from the Hong Kong study



Map 17. **Neighborhood-level ROI for Hong Kong** (temperature reduction).

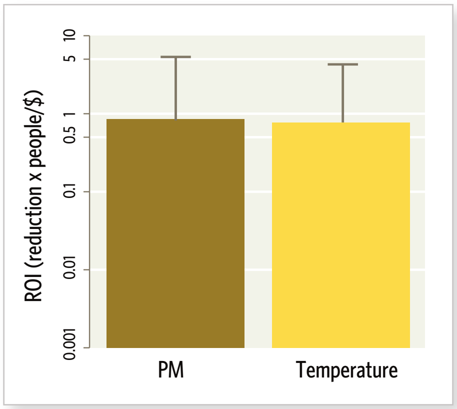


Figure 22. ROI for tree planting for Hong Kong.

PM ROI

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Higher Return Lower Return

Investment	**Annual Cost ($)**	**> 1 ug/m^2 PM$_{2.5}$***	**1.5 deg C**
10% of sites	152,000	290,000	324,000
20% of sites	294,000	503,000	531,000
Full Investment	1,280,000	1,010,000	1,010,000

*Note: Most people will receive a reduction of > 10 ug/m^2 PM$_{2.5}$ in this city

Table 10. Temperature and PM reduction benefits under three investment scenarios for Hong Kong.

Photo © iStock, Warren Goldswain

JAKARTA

Anyone moving to Jakarta quickly learns a key phrase in Bahasa: “Kena macet.” It means “(I) get stuck in a traffic jam.”

Jakarta has the worst “macets”—traffic jams—in the world, at least according to an index developed by the oil company Castrol, which measured how often drivers stop and start. According to that analysis, drivers in Jakarta are stopping and starting their cars 33,240 times per year on the road. That is more than twice as often as New York, the worst US city on the list. Traffic is so bad that Indonesia’s previous President, Susilo Bambang Yudhoyono, proposed moving the capital out of Jakarta.

The traffic problems stem largely from the rapid growth of the city. Central Jakarta has a population of more than 10 million in an area of just over 25 square miles. This figure understates the challenge, however the challenge, however. Central Jakarta, also called the Special Capital Region of Jakarta, is just part of a sprawling megacity known as Jabodetabek—taken from the initial letters of the administrative units of Jakarta, Bogor, Depok, Tangerang and Bekasi—that covers some 2,300 square miles and is home to 28 million people.

Over the past century, the population of Jakarta and its surrounding area has increased nearly 200-fold. By 2010, the megacity housed 12 percent of Indonesia’s total population on less than 0.3 percent of the country’s total area.

Jakarta’s infrastructure has struggled to keep pace with the growth, particularly regarding transportation. Jakarta, for example, is the largest city in the world without a metro system. Other major cities in Southeast Asia with smaller populations than Jakarta have had metro systems for years, including Manila (1984), Singapore (1987), Kuala Lumpur (1995), and Bangkok (2004).

All of Jakarta’s cars, trucks, and buses, along with cooking fires, kerosene, and heavy industries, combined to burden the city with some of the most severe air pollution problems in the world in the 1960s and 1970s. In response, the government began phasing out the use of leaded gasoline in 2001 and eliminated the use of lead in 2006, began car emissions checks in 2007, and pushed power plants to switch from diesel to compressed natural gas in 2010. Those steps helped clear the air: Today there are more days when the skies are clear enough to see the lush mountains of the province of West Java, 30 miles south of the city center.

The blue skies do not, however, tell the whole story. While cars have gotten cleaner, they still emit fine particles, and Indonesia’s booming economy over the past decade means that millions more people can afford cars: nearly 500,000 new cars in 2014 alone, along with 1.4 million new motorcycles. All those new vehicles are effectively swamping the benefits of the pollution control laws. So while skies appear clearer, air quality, as measured by $PM_{2.5}$ levels, has actually gone down.

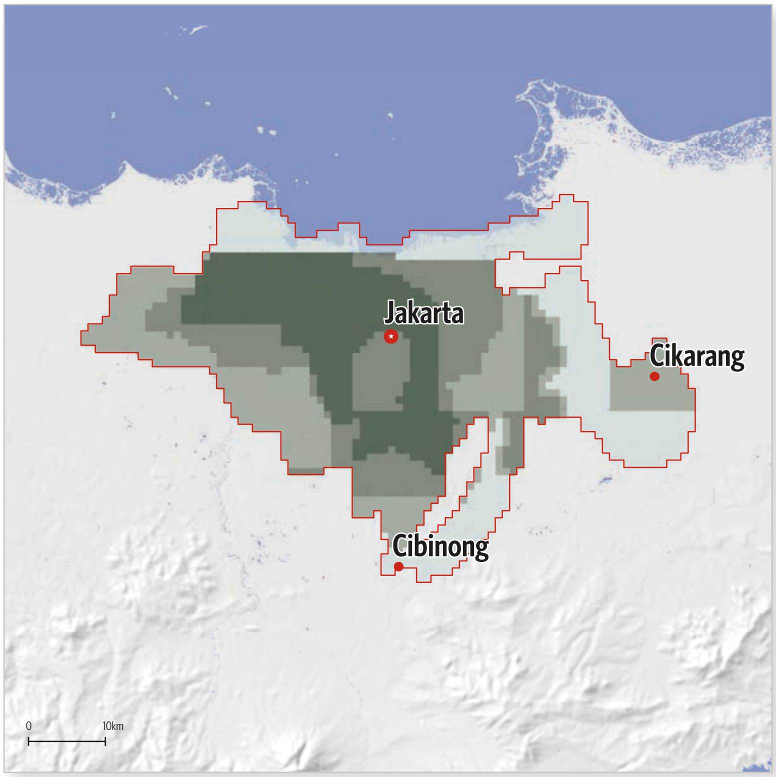
Another, far more visible problem also looms for Jakarta. Indonesia is the world’s largest producer of palm oil, and fires are frequently intentionally lit to clear land for new palm plantations. The illegal burning of forests and agricultural land, combined with a prolonged dry season and the impact of El Niño, has led to more than 100,000 fires across Indonesia since early 2015, some of which are peat fires that may burn for months or even years. The smoke has blanketed much of Southeast Asia in an acrid haze, with one estimate that daily CO_2 emissions from the fires have surpassed the average daily emissions of the entire U.S. economy.

The city of Palangkaraya, on the island Kalimantan, across the Java Sea from Jakarta, recorded PM$_{10}$ levels of 1,357 micrograms/m^3—far above the healthy level. A spokesman for Indonesia's Meteorology, Climatology and Geophysics Agency called the fires as "a crime against humanity."

There are some hopeful signs that the government is tackling the fires and the broader pollution problem. The government is seeking to restore degraded peat land and to prosecute corporations that cleared land illegally. The government is also mandating that the auto sector improve emission standards on new vehicles to meet European levels starting in 2017. Monitoring has also improved: The Meteorology, Climatology and Geophysics Council now collects data from eight monitoring stations across Jakarta to measure air quality minute by minute.

Improved mass transit and increased efforts to create more green space in the city could be part of longer-term plans to improve air quality in Jakarta. As a high-density city, Jakarta has a high ROI relative to other cities. The center neighborhoods have the highest density and hence the highest ROI. For an annual additional investment of $1.7 million in street tree planting, more than 700,000 people could get at least a 1 µg/m^3.

Results from the Jakarta study



Map 18. Neighborhood-level ROI for Jakarta (PM reduction).

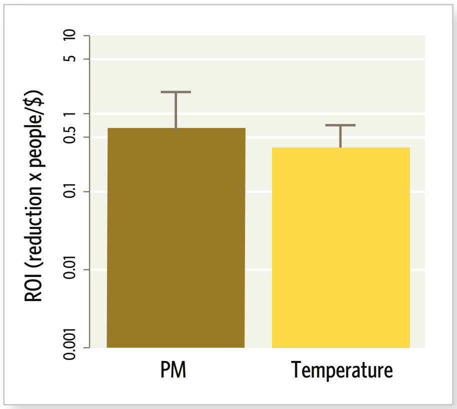


Figure 23. ROI for tree planting for Jakarta.

Investment	Annual Cost ($)	> 1 ug/m^2 PM$_{2.5}$	1.5 deg C
10% of sites	1,660,000	761,000	772,000
20% of sites	3,220,000	1,280,000	1,350,000
Full Investment	16,200,000	3,680,000	3,680,000

Table 11. Temperature and PM reduction benefits under three investment scenarios for Jakarta.

JOHANNESBURG

Photo © iStock, THEGIFT777

For decades, the sprawling townships around Johannesburg, South Africa's largest city and economic hub, stood as a blazing testament to racial injustice. Established in the 19th century as camps for laborers in newly discovered gold mines, the townships did not come to world attention until they became the wellspring of protest against the apartheid system, imposed in the late 1940s.

The townships—most famously Soweto but also places like Tembisa, Vosloorus Katiehong, and Meadowlands—were symbols of racism—then a symbol of resistance. Today they may be a symbol of rebirth.

Under apartheid, the townships were officially little more than way stations. Until 1976, township population could have status only as temporary residents. Black laborers would inhabit the square, four-room brick dwellings derisively called "matchbox houses" only while their employment contracts were valid. They were supposed to live in the townships solely to work for white residents in Johannesburg and other nearby cities. The government gave little thought to providing infrastructure of any kind for township residents.

Elsewhere in the city, however, Johannesburg's residents had been busily remaking the landscape for generations. The city lies in a region known as the Highveld, a typical African savannah/grassland ecosystem with few trees. Early settlers planted trees for fodder, fuel, fruit, and wood production, but things changed dramatically with the gold rush in 1886. The miners needed thousands of wooden props for the tunnels, so they established huge plantations of Blue Gums, a species of Eucalyptus native to Australia. Over a million trees were planted in what is now Saxonwold, a suburb of Johannesburg.

As the city grew, the tree planting spread beyond the Blue Gum plantations and the streets and gardens of white Johannesburg filled with trees. In 1904, the first street trees were planted in Johannesburg's town square, and by the early 1990s, an estimated 6 million trees had been planted within the boundaries of the old Johannesburg and 10 million collectively within the modern city boundaries.

Today Johannesburg boasts 50,000 acres of green space and open space in more than 2,000 public parks. There are so many trees today that the oft-repeated claim is that Johannesburg is the largest man-made urban forest in the world. The data for that claim are slim, but it is beyond question that Johannesburg's 6 million trees make it a cool, pleasant, and shady. But not for everyone.

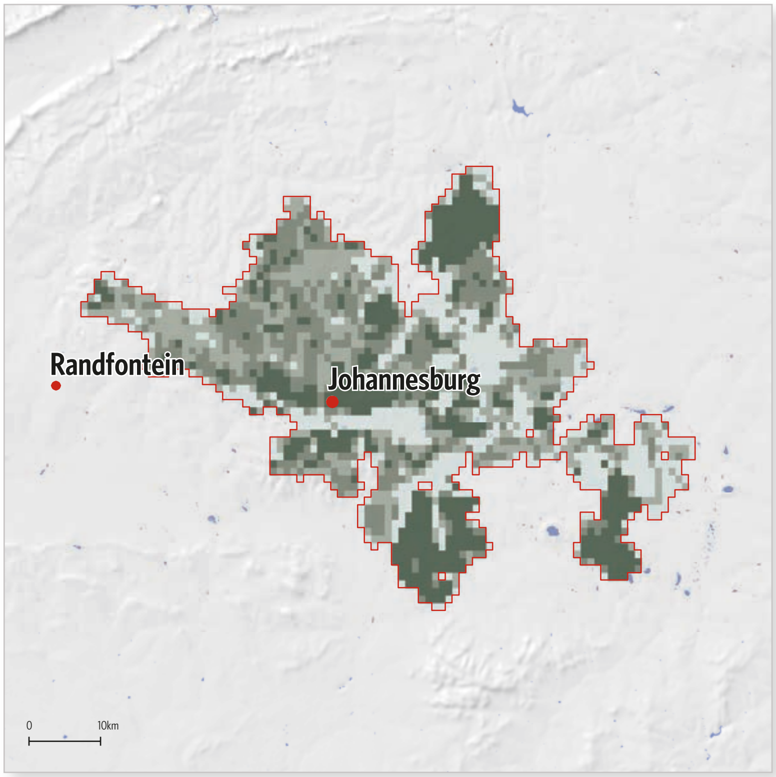
The green canopies that travelers see from the air are the wealthy, former white-only northern suburbs. The poorer townships are closely packed with houses and surrounded by the treeless veld.

Few trees were planted in Soweto or any other township. But the need for more trees is becoming clearer every day. Climate model projections for Johannesburg indicate that the local climate is likely to become both significantly hotter and more humid. The models suggest that temperatures for the city may increase by around 2.3° C by over the next 40 years and by more than 4° C over the next 70 years or so.

Since 2006, however, there has been a massive effort to extend Johannesburg's urban forest. The Soweto Greening Project, for example, began that year with 6,000 trees being planted. The aim is to plant 200,000 trees throughout the township.

Johannesburg has even more far-reaching plans to expand the amount of green space across the city. Our study did not include Soweto, but it does cover parts of other townships. Johannesburg is only moderate in ROI for tree planting, compared to other cities globally. However, there are scattered neighborhoods with very high potential. For an additional $500 thousand annually in street tree planting, more than 100,000 people could have a reduction of 1.5° C (2.7° F) in summertime temperatures.

Results from the Johannesburg study



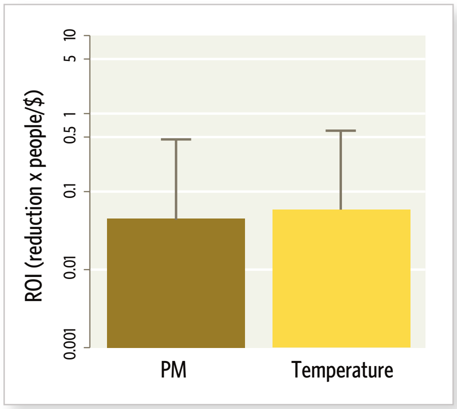


Figure 24. ROI for tree planting for Johannesburg.

PM ROI

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Higher Return … Lower Return

Map 19. Neighborhood-level ROI for Johannesburg (PM reduction).

Investment	Annual Cost ($)	> 1 ug/m^2 PM$_{2.5}$	1.5 deg C
10% of sites	488,000	127,000	140,000
20% of sites	899,000	157,000	191,000
Full Investment	2,970,000	211,000	258,000

Table 12. Temperature and PM reduction benefits under three investment scenarios for Johannesburg.

Photo © iStock, ImageGap

LONDON

Friday, December 5, 1952, began as an average winter's day in London, clear and cold. It had been unusually cold for the previous week, so many households shoveled more coal into the furnace. Most of England's supply of hard, anthracite coal was sold for export to pay off the country's war debt, leaving people in London to burn the softer, high-sulphur, bituminous variety.

During the night, a mass of cold air had moved over the city, creating an inversion and trapping warm air plus all the smoke from homes, factories, and traffic at the surface. By mid-day East Londoners could not see their feet. For five days banks of dense yellow fog smothered London. Cars, trains, and buses stopped running. Businesses, restaurants, and theaters closed, trapping people in their homes, but the choking cloud even seeped under doorways.

Thousands of people were treated at hospitals for respiratory problems. Official estimates at the time put the number of fatalities at 4,000—more civilian casualties than any single incident during the war. Recent research, however, suggests that what became known as the "Great Smog" may have caused as many as 12,000 deaths.

London had a long history of these so-called "pea-soupers." The legendary London fog was not fog at all, but choking smog, mostly particulate pollution from coal fires. The Great Smog of 1952, however, was the worst ever, and it was a turning point. It led to a major cleanup of city air quality and the passage of a revolutionary clean-air law in 1956, seven years before the U.S. Clean Air Act.

The new law banned the burning of polluting fuels in "smoke control areas" across the United Kingdom. The results were dramatic: a hundred-fold decrease in atmospheric particulate levels. Public health was vastly improved; flora and fauna that had all but vanished from urban places by the 1950s began to flourish; and the grand architecture of Britain's cities was no longer obscured beneath a thick layer of soot and grime.

London now has an expanding public transportation network. The first section of Crossrail, a 118-kilometre (73-mile) railway line linking London and Berkshire, Buckinghamshire, and Essex counties, will open in 2018; there is a thriving bike share program; and drivers must pay a congestion charge of £11.50 ($15) to drive into the city. Yet, while pea-soupers are a thing of the past, pollution persists.

Some of London's air-quality problems are an unintended consequence of efforts to fight climate change. In 1998, European car makers committed to reducing CO_2 emissions by 25 percent, and as as result, the European car fleet switched from largely gasoline to predominant diesel, because diesel emits less carbon dioxide. Diesel, however, produces significant amounts of both particulates and NO_2—enough to swamp London's pollution-reduction efforts even as CO_2 emissions fall.

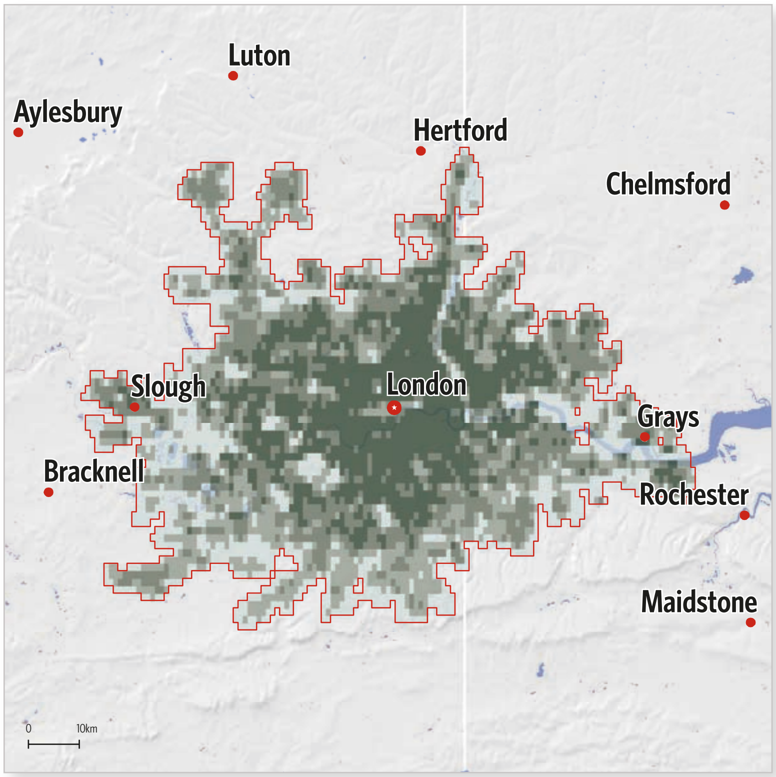
In 2014, the government agency, Public Health England, said that $PM_{2.5}$ probably killed more than 3,000 people in London in 2010. That was down from previous studies, but still worrisome.

Nitrogen dioxide is an even bigger problem, with levels in London that are among the highest anywhere in the world.

The 2014 statistics suggest that London and southeast England have by far the worst air in Britain, largely due to traffic levels. In London, in addition to death attributable to particulate pollution, more than 40,000 "life years" were lost in 2010. In southeast England, more than 4,000 people died and almost 42,000 years were lost.

London has moderate median ROI for tree planting, relative to other cities internationally. The neighborhoods with the highest ROI are in the center portion of the city, which is relatively higher density. For an additional annual investment of $18 million in street tree planting, we estimate that 1.5 million people could have a > 1 µg/m^3 reduction in PM.

Results from the London study



Map 20. Neighborhood-level ROI for London (PM reduction).

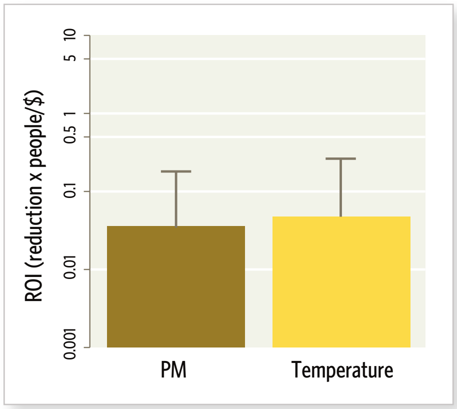


Figure 25. ROI for tree planting for London.

PM ROI

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Higher Return Lower Return

Investment	Annual Cost ($)	> 1 ug/m^2 PM$_{2.5}$	1.5 deg C
10% of sites	1.77E+7	1,570,000	2,440,000
20% of sites	3.52E+7	2,870,000	3,910,000
Full Investment	1.52E+8	5,840,000	7,260,000

Table 13. Temperature and PM reduction benefits under three investment scenarios for London.

London is planning other aggressive steps to improve its air quality. In addition to the congestion charge, London has a Low Emissions Zone, which charges trucks and buses that do not meet EU emission standards for particulates a fee of up to £200 ($280) per day. An even stricter Ultra Low Emissions Zone is planned for 2020 that would require all vehicles, including cars and motorcycles, to meet the emissions standards or pay the £200 fee. By 2018, new models of London's iconic black cabs will have to be electric, the first time any city has proposed to develop a zero-emissions cab fleet. The first fully electric double-decker bus hit the streets in the fall of 2015.

LOS ANGELES

Photo © iStock, NYCstocker

The largest El Niño event ever recorded was supposed to dominate the news in Los Angeles in early 2016. So large it was dubbed Godzilla El Niño, the enormous swath of unusually warm Pacific Ocean water, some 6 million square miles in area, was anticipated to bring drenching rains to the city, and many feet of snow to the mountains.

Nearly everyone in Southern California was waiting to welcome El Niño with open arms. A record-setting deluge was just what was needed to break, or at least put a dent in, a crippling, four-year year drought.

El Niño brought some relief, especially to northern and central California, and some reservoirs, such as Shasta, the state's largest, are at or near capacity. Los Angeles was not so fortunate. After the last severe drought, from 1987 to 1991, Southern California increased its water storage capacity 14-fold. All that storage eased the pain of the current drought, but now, despite El Niño, reservoirs near Los Angeles are still less than half full.

The link between climate change and drought are intriguing but still speculative. The daunting prospect for Angelenos, however, is the possibility that climate has tipped to a new and lasting condition, marked by little rain and rising temperatures. That future became reality in the winter of 2016.

Typical February temperatures in Los Angeles is about 70 degrees. On February 7, 2016, the temperature reached 89 degrees at Los Angeles International Airport, a new record for the day. Another bout of record-breaking heat hit the city a few weeks later.

All this would usually be of little concern to anyone except the record-keepers and weather junkies. In this case, however, it is part of a worrisome trend. The late winter heat waves followed on fall weather that was even hotter. In early October 2015, downtown Los Angeles hit 100 degrees on back-to-back days. The sweltering 100-degree stretch was the longest in 25 years and matched the longest ever recorded in October. The heat stressed electricity generation, and at least 9,000 people were without power.

The combination of heat and extreme drought spell trouble for air quality in Los Angeles through a complex chain of events. Prolonged dry spells bring more temperature inversions, with a layer of warmer air trapping cooler air below, concentrating pollution near the ground. Higher temperatures accelerate the chemical reactions that form ozone, a key ingredient in smog, while also boosting demand for electricity, which further increases the smog-forming emissions from power plants. Hot, dry weather also creates ideal conditions for wildfires, which release still more smoke and soot. Meanwhile, in the Central Valley north of the city, dry farmland has been kicking huge dust clouds into the air.

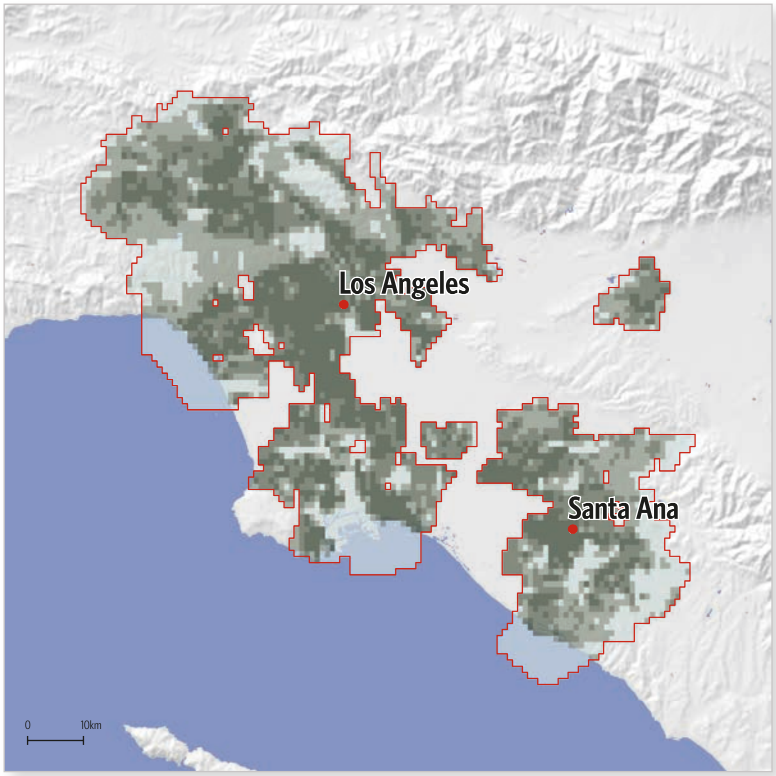
If the warm, dry trends continue, as most experts predict, California's decades-long progress in improving its air quality may be in danger. Since the 1980s, peak ozone concentrations in Southern California have fallen by about two-thirds, and fine-particle pollution has been cut in half since 1999. Emissions from cars, trucks, ships, power plants, and industrial facilities are also falling. About 63 percent of Californians now live in areas that meet federal health standards for ozone, compared with 24 percent in 1990, according to estimates by the state Air Resources Board.

Yet California still has a long way to go before it meets federal air-quality standards and its own ambitious climate goals. Reducing ozone to federally mandated levels by 2032 will require deploying low- or zero-emissions technology across the economy, and particularly in the South Coast Air Quality Management District, which includes 16.7 million people in Los Angeles, Orange, Riverside, and San Bernardino counties.

Given the long-term threat that increasing temperatures due to climate change poses to air quality, state regulators are looking into new rules as well as new strategies to reduce emissions of greenhouse gases at the local level. Those strategies could target short-lived pollutants like methane; encourage dense development near transit stations; or fund solar water heaters, electric vehicle charging stations, and other carbon-cutting projects.

The results of this study also indicate the role the trees can play in the larger strategy for Los Angeles. While at a city-level, the median ROI of tree planting is only moderate by global standards, there are specific neighborhoods that would have high ROI, including dense neighborhoods in central Los Angeles, Santa Monica, and Long Beach. For an additional annual investment of $6.4 million in street tree planting, we estimate that more than 400,000 people could have a reduction of 1.5° C (2.7° F) in summertime temperatures.

Results from the Los Angeles study



PM ROI

▇ ▇ ▇ ▇

Higher Return Lower Return

Map 21. Neighborhood-level ROI for Los Angeles (temperature reduction).

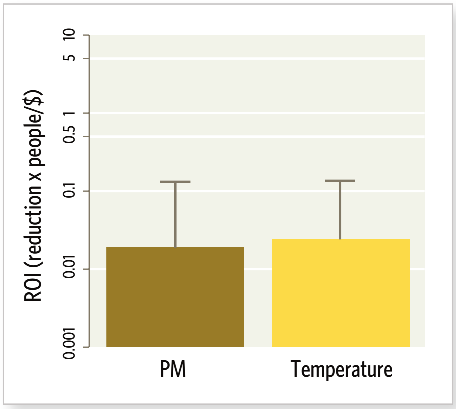


Figure 26. ROI for tree planting for Los Angeles.

Investment	Annual Cost ($)	> 1 ug/m² $PM_{2.5}$	1.5 deg C
10% of sites	6,360,000	432,000	437,000
20% of sites	12,700,000	695,000	702,000
Full Investment	51,600,000	1,300,000	1,320,000

Table 14. Temperature and PM reduction benefits under three investment scenarios for Los Angeles.

MEXICO CITY

Photo © iStock, MartinM303

Hoy No Circula—No Driving Today. That is the message that at least 20 percent of drivers in Mexico City get every day. If pollution levels spike, the number can double. In an effort to crack down on the city's long-standing pollution problem, in 1989 the national government enacted a plan to limit the number of cars driving into the city.

The government had ample reason to take such a step, and more. For decades Mexico City had some of the worst air pollution in the world. There were reports of birds dying in mid-flight and dropping from the sky. Children colored the sky gray, because they never saw anything else. In 1992, Mexico City earned the dubious distinction of being number one on the United Nation's list of the 20 most polluted cities.

The sheer size of the city is one problem. With 9 million people in the city proper, and roughly 21 million in the surrounding Valle de Mexico, it is the most populous urban area in the western hemisphere. Migration from other parts of Mexico has slowed in recent years, but the city will still add millions of more residents by 2020.

The geography of Mexico City compounds the pollution problems. It lies on what was once an enormous lake, the floor of an ancient crater surrounded by mountains, including an active volcano, Popocatépetl. Eruptions, the last of which occurred in the spring of 2016, add even more dust and ash to the atmosphere.

Mexico City sits at over 7,000 feet in elevation. The lower level of oxygen reduces the efficiency of vehicle engines, so they are more polluting. Finally, warm air frequently settles above the valley, creating an inversion that seals in the pollution.

In the 1990s, the Mexican government developed a comprehensive plan called ProAire to tackle the problems. *Hoy No Circula* is one element, and keeps as many as 2 million cars at home. As part of ProAire the city also tests vehicles for compliance with emissions regulations; requires all new cars to have catalytic converters; reduced the levels of sulphur in diesel fuel; increased the number of buses powered by natural gas; built dedicated bike lanes; and retired 1,500 of the most polluting small and medium-size buses. Mexico City has expanded its public transit options, and it has the largest bike-sharing program in the region.

ProAire was so successful at reducing pollution that in 2013, the C40 Cities Climate Leadership Group awarded Mexico City its air-quality prize. The award noted the diversity of actions but also the impressive achievement of reducing ambient air concentrations of primary pollutants, including 97 percent of lead emissions, 89 percent of SO2, 79 percent of CO_2 and 66 percent of PM_{10}, over a 25-year period.

Over the past several years, however, improvements in air quality have slowed, or even reversed. In early 2016, authorities declared the first air-pollution warning since 2005 and pronounced an environmental emergency. Two months later, with no end to the crisis in sight, the city banned about 40 percent of the more 5 million vehicles that daily transit the city and suburbs.

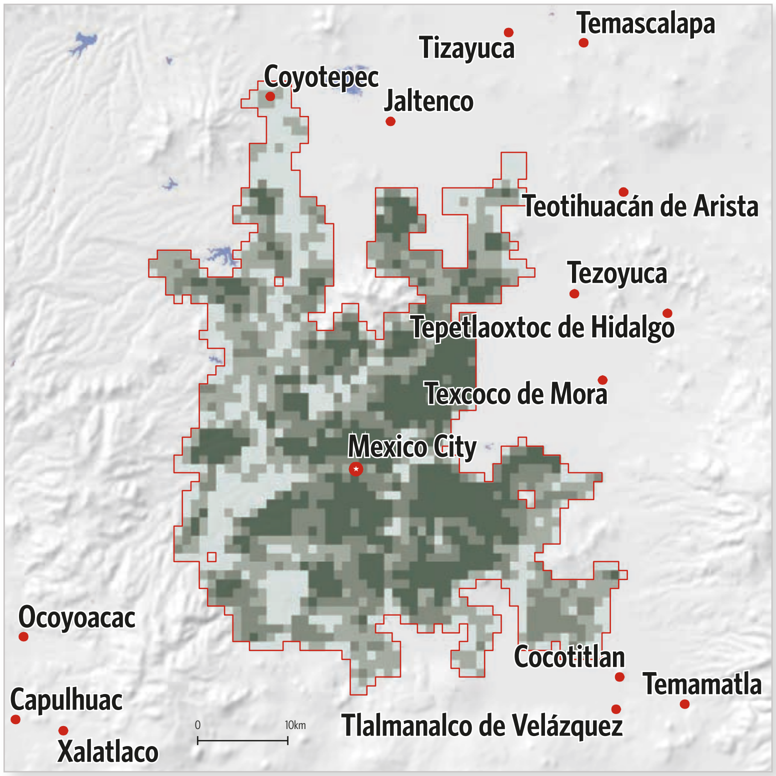
Continued population growth, increased automobile traffic, and industrial activity—along with inconsistent enforcement of environmental laws—have undercut some of the gains Mexico City has made. Hoy No Circula has, ironically, created an incentive for people to own more than one car: The system is based on the last digit of the car's license plate, so as long as the two plates do not match, then the owner can get around the one-day driving ban.

Federal and municipal officials have vowed to take new steps to reduce pollution, including tighter emissions controls and a crackdown on cheaters. Promoting new technologies for more efficient energy use in buildings and offering tax incentives for sustainable construction and green roofs are among the other initiatives Mexico City has undertaken.

Reforestation and creation of green areas will help as well, and the city has committed to collecting the necessary data. In January 2014, the Mexico City government started a real-time monitoring program to determine black carbon concentrations at five sites across the city.

Mexico City has, compared to other cities globally, a moderate ROI of tree planting. The neighborhoods with the highest ROI are in central and east Mexico City. Moreover, our estimate of planting cost was relatively low for Mexico City, which increases the ROI shown in the scenarios in the table.

Results from the Mexico City study



Map 22. Neighborhood-level ROI for Mexico City (PM reduction).

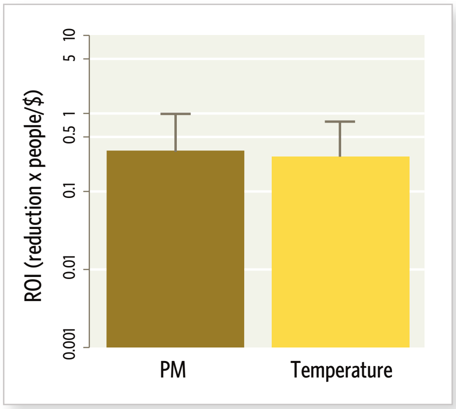


Figure 27. ROI for tree planting for Mexico City.

Investment	Annual Cost ($)	> 1 ug/m^2 PM$_{2.5}$	1.5 deg C
10% of sites	430,000	203,000	205,000
20% of sites	861,000	358,000	361,000
Full Investment	3,850,000	869,000	869,000

Table 15. Temperature and PM reduction benefits under three investment scenarios for Mexico City.

Photo © AWL Images / Masterfile

NAIROBI

Nairobi is one of few world capitals to boast a national park within its borders. Lying to the south of the downtown area, Nairobi National Park, created in 1946, is the only place in the world where tourists can take a photo of a lion or a giraffe or even a black rhinoceros with skyscrapers looming in the background.

The park covers some 45 square miles of open plains, broken bush, the Athi River and its deep gorges, long grass, short grass, flat land and foothills, and, in the western uplands, the Kisembe Forest. For Nairobi, the forest may be the most important habitat in the park.

Kisembe forest is, in fact, the southern fringe of what used to be the extensive Langata Forest and is comprised of Crotons (e.g., *Croton dichogamus),* African olive *(Olea africana),* Muhugus (e.g. *Brachylaena hutchinsii),* Cape Chestnuts (*Calodendrum capense*) and other indigenous species. One of few remaining large expanses of tree cover in Nairobi, it is sometimes called the "lungs of the city."

Whether the forest will continue to play that role is an open question. Kisembe, and indeed the entire park, is threatened by the rapid and largely unplanned expansion of Nairobi, one of the fastest-growing cities in all of Africa.

The larger Nairobi metropolitan area had a population of 6.1 million in 2007, which is projected to rise to over 12 million by 2030. Much of this growth is occurring as sprawl, as areas on the city edge absorb spillovers from the central city, where scarce rental housing is increasingly unaffordable to average citizens. This growth, combined with a lack of investment in public transport and urban road infrastructure, has resulted in increasing road deterioration, numbers of motor vehicles, and congestion.

Millions of Nairobi's residents (up to half the population, by some estimates) live in informal settlements: shanty towns and slums with few or no services, bad roads, and little access to clean water. Open cooking fires are common, as are trash fires. The city also has limited public transportation, so people living in the informal settlements rely on a huge fleet of privately run minibuses called *matatus*. Not only are they dangerous—*matatus* with riders dangling out the windows of even on the roof are a common sight downtown—they tend to be old and poorly maintained, so they spew pollution across the city. Add the fact that the lack of roads means the *matatus* and the thousands of diesel trucks and buses entering the city everyday often sit idling in epic traffic jams and you have a recipe for choking smog.

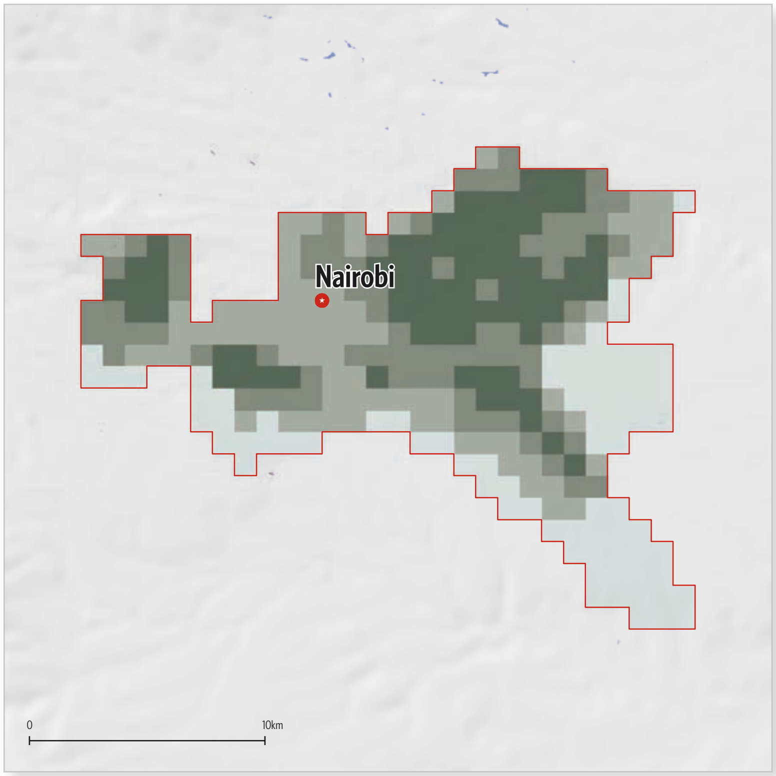
Nairobi is attempting to address the problem in several different ways. First, in 2014, the Kenyan National Assembly enacted progressive and robust air-quality regulations intended to curb pollution of air by vehicles, factories, and other sources by ensuring minimum air-quality standards for both mobile and stationary sources. When fully enforced, industries using old and inefficient technologies will be required to adopt improved emission-reduction technologies or transition to cleaner industrial processes.

Nairobi also has an ambitious plan for future development called Nairobi Metro 2030. Largely focused on improving the city's international economic competitiveness, it outlines the development of a transport master plan to improve transportation infrastructure and land use planning, including an urban mass-transit strategy that centers around investments in high-occupancy buses and modernization of the existing commuter rail network. How effectively the municipal and national governments, often plagued with corruption and dissent, will translate the vision of the plan into tangible improvements for Nairobi's residents remains a largely unanswered question.

Some of Nairobi's efforts to solve the traffic congestion problem may be at least partly self-defeating. A major new highway, the Nairobi Southern Bypass, and an expansion of a railway line threaten to slice through Nairobi National Park, and Kisembe Forest, in particular. In response, the Kenya Wildlife service in partnership with private companies is managing the Green Line Project, an initiative to plant forest along 30 kilometers of the perimeter of the park. The hope is to create a visible boundary between the park and surrounding new developments, and to discourage lobbying by developers to cut slices off the park. The program, which began in 2010, is part of a broader effort created by the late Nobel Prize winner Wangari Maathai to plant new trees throughout Nairobi to improve water catchment and biodiversity.

Compared to other cities globally, Nairobi has a moderate ROI of tree planting for PM removal. Neighborhoods in the center and northeast of the city have the highest ROI. Because PM$_{2.5}$ concentrations are relatively low in Nairobi, according to the global dataset we used, we estimate that the absolute reduction would be less than 1 µg/m^3 for most people.

Results from the Nairobi study



Map 23. Neighborhood-level ROI for Nairobi (PM reduction).

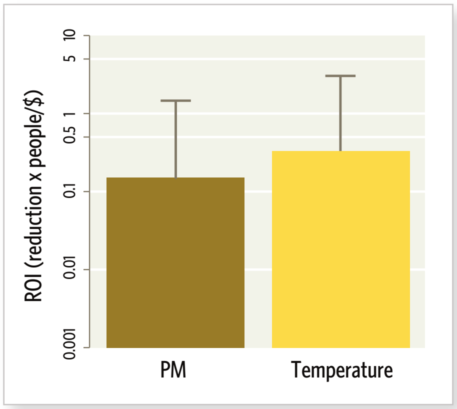


Figure 28. ROI for tree planting for Nairobi.

Investment	Annual Cost ($)	> 1 ug/m^2 PM$_{2.5}$	1.5 deg C
10% of sites	158,000	0	267,000
20% of sites	311,000	0	406,000
Full Investment	1,520,000	0	683,000

Table 16. Temperature and PM reduction benefits under three investment scenarios for Nairobi.

Photo © iStock, David Sucsy

NEW YORK

In 1913, Joyce Kilmer composed his best-known poem and perhaps the most famous ode to nature ever written. It begins with these lines, memorized countless times by countless schoolchildren:

I think that I shall never see
A poem lovely as a tree.

So it was more than fitting that, 102 years later, a park in New York City named for Joyce Kilmer was the site of a ceremony to cap an eight-year effort to plant 1 million trees across the city. Kilmer would no doubt have smiled.

New York began the MillionTreesNYC initiative under then-Mayor Michael Bloomberg in 2007, and the goal was to finish in 10 years. With the support of Bloomberg and his successor, Bill DeBlasio, the city reached its goal two years early.

The one-millionth tree—an 8-year-old, 25-foot-tall lacebark elm—was planted in Joyce Kilmer Park, a baseball toss from Yankee Stadium in the South Bronx, one of the poorest areas of the city. A half-dozen such neighborhoods, devoid of trees and reporting high rates of asthma, were singled out for mass plantings as a part of the city-wide effort to create new green space and to combat the effects of climate change.

Before launching the million trees initiative, the New York City Department of Parks and Recreation identified neighborhoods most in need of trees by overlaying urban canopy maps with community health survey maps. Unemployment, low incomes, the rate of hospitalization for asthma for children for 14 and younger—all correlated with the absence of trees. From this data, the agency designated six "Trees for Public Health" neighborhoods to receive canopy management plans and targeted planting: Hunts Point and Morrisania (location of Joyce Kilmer Park) in the Bronx, East New York in Brooklyn, East Harlem in Manhattan, Stapleton in Staten Island, and The Rockaways in Queens.

Other cities have set similar goals for planting trees, but have had limited success. Denver abandoned its Mile High Million campaign in 2013, while Los Angeles got less than halfway through its Million Trees LA effort. But in New York, with the help of thousands of volunteers, MillionTreesNYC was able to plant 20,000 saplings a season in forests, restoring 700 acres citywide.

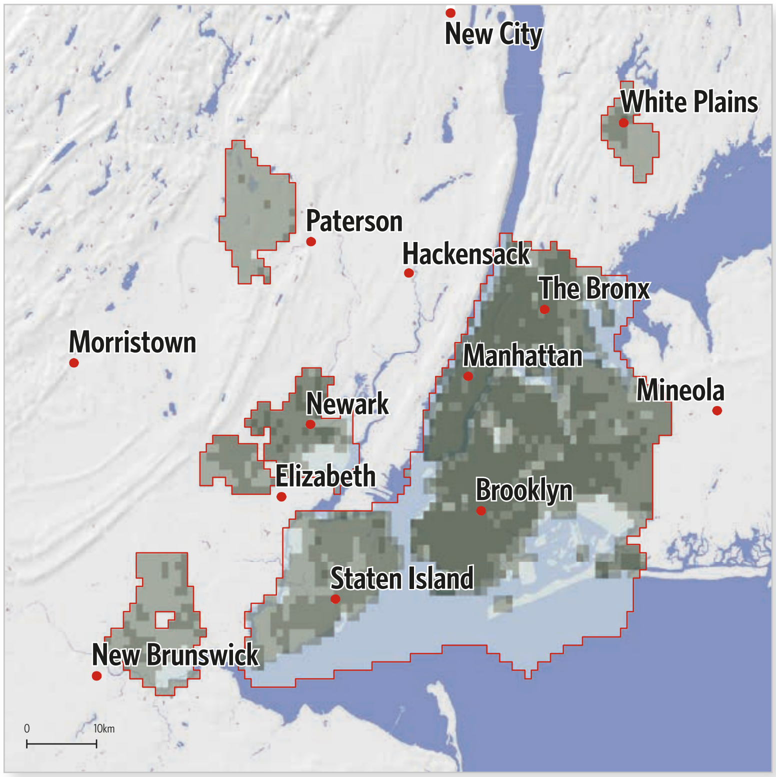
Three-quarters of the trees planted as part of the initiative were added to city property like existing parks, along with 220,000 new street trees in all five boroughs, To get new trees into other public and private space—around hospitals, libraries, churches, public housing developments and in private yards—the city teamed up with the New York Restoration Project, brainchild of actress and singer Bette Midler. Together they raised $30 million toward the tree plantings. Over the course of the project, the city expanded its number of trees by 20 percent.

New York City now has some 5 million trees. Trees cover almost a quarter of the city, and there are more than 6,000 acres of woodlands in city parks alone. The city will need every one of those trees, and even more. Climate change is coming: Temperatures in New York are expected to jump 4.1 to 5.7 degrees by the 2050s, and by the 2080s, it could be 8.8 degrees hotter than the current average of 54 degrees, according to the study by the New York City Panel on Climate Change, a group of leading scientists assembled by the city.

According to the panel's report, by mid-century, the city could get five to seven heat waves a year, compared to two currently, and the number of days over 90 degrees could double. The mercury is expected to crack 100 three to five days a year, compared to the current rate of less than once every year.

New York has developed a comprehensive plan to deal with the consequences of climate change, particularly the risk of catastrophic floods. Among the initiatives in the plan, A Stronger, More Resilient New York, released in 2013, is a commitment to improve the health and resiliency of the city's urban forest, recognizing the array of health and environmental benefits that trees provide. While New York City has a dense urban core where the ROI of tree planting is high, the farther suburbs and outlying towns have a lower ROI. We estimate that for an additional annual investment of $12 million in street tree planting and maintenance, more than 2.8 million people could have a reduction of 1.5° C (2.7° F) in summertime temperatures.

Results from the New York study



Map 24. Neighborhood-level ROI for New York City (temperature reduction).

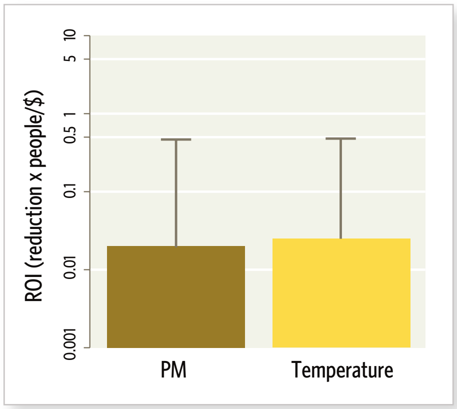


Figure 29. ROI for tree planting for New York City.

PM ROI

🟩 🟩 🟩 🟩

Higher Return Lower Return

Investment	Annual Cost ($)	> 1 ug/m^2 PM$_{2.5}$	1.5 deg C
10% of sites	12,200,000	2,650,000	2,790,000
20% of sites	24,400,000	3,810,000	4,180,000
Full Investment	85,800,000	5,290,000	5,920,000

Table 17. Temperature and PM reduction benefits under three investment scenarios for New York City.

Photo © iStock, AndreyGorulko

PARIS

Parisians call the Champs Elysees La Plus Belle Avenue du Monde—the most beautiful avenue in the world. The Mayor of Paris, Anne Hidalgo has another name for the grand, 1.25-mile avenue from Place de la Concorde down to the Arc de Triomphe. She calls it "a canyon of pollution."

That is a relatively recent development. For decades, few observers would have put Paris among the most polluted cities in Europe, let alone the world. But that has changed. In 2014, air pollution in Paris hit health-threatening levels, more than 80 percent higher than in London and Berlin. In the spring of that year, according to the European Environment Agency, on at least one occasion the PM_{10} level hit 147 micrograms per cubic meter of air in Paris, compared with 114 in Brussels, 104 in Amsterdam, 81 in Berlin, and 80 in London. A year later, the situation was even worse, as Paris briefly held the distinction of the city with the most polluted air in the world. The city's iconic monuments were shrouded in haze.

Vehicle exhaust is the primary culprit, responsible for two-thirds of the city's nitrogen dioxide pollution, which produces ozone, and more than half of the city's particle pollution. In 2014, the city instituted alternate driving days (only odd- or even-numbered license plates permitted) and temporarily eliminated fares on all public transportation.

Those steps had limited impact, so Mayor Hidalgo went further. As an experiment, she decided to ban cars from key areas of the city, including the Champs Elysses, for seven hours one day in the fall of 2015. According to air-quality network Airpartif, which monitors pollution levels in Paris, there was a 40-percent drop in harmful exhaust emissions in parts of Paris.

The success of that one-day experiment led to a broader campaign, called Paris Breathes. Some two dozen routes in the city will now be car-free on the first Sunday of every month. Another four zones will also be pedestrian-only on Sundays during summer months.

In July 2016, Paris banned old cars from its streets in a further bid to crackdown on air pollution.

Any car registered before 1997—excluding vintage vehicles—will be barred in the city center on weekdays between 8 a.m. and 8 p.m. Any car owner caught breaking the rules will be issued a €35 fine for their first offense, with the fines set to nearly double early next year.

By 2020, Mayor Hidalgo says, the ban could be extended to include all combustion-engine cars manufactured before 2011. More than a half-million car owners in Paris are expected to be affected.

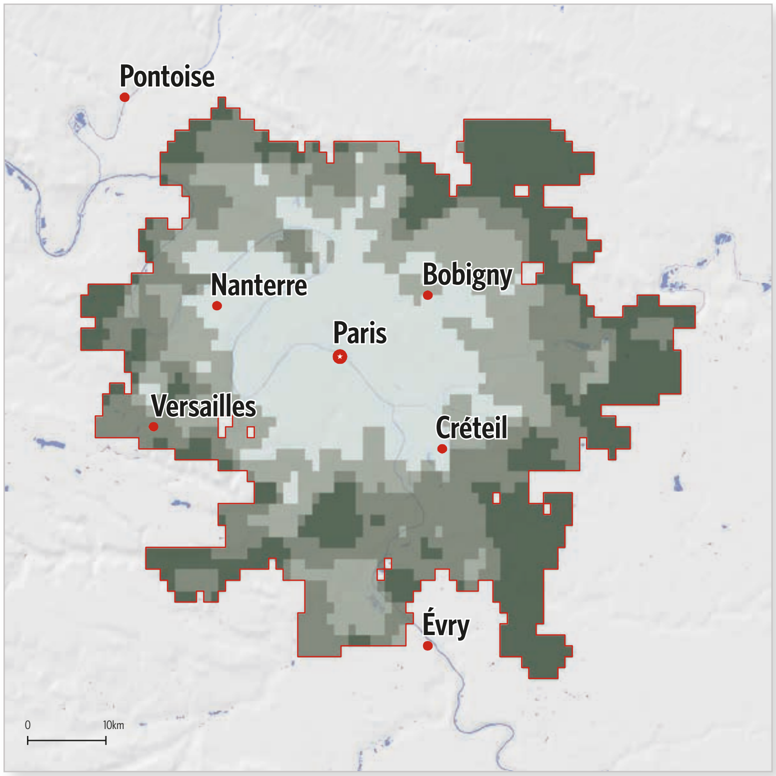
The efforts to clear the air in Paris go beyond just changing how Parisians drive. In Place de la Nation, one of the city's famous squares, are three steel-sided structures, about 13 feet all and several feet thick. Free standing, with a curved, brushed-steel foot and a bench on one side, each one almost looks like it might be a piece of public sculpture, a frame for a large advertisement, or an electronic message board. You would not, at a glance, mistake it for a tree. But in an important sense, that is exactly what it is.

The vertical face of the structure is not intended for words or pictures, but rather for moss. Outfitted with sophisticated air pollution monitors and connected to the internet, it is in effect a high-tech tree, built with the sole purpose of scrubbing fine dust and nitrous oxides from the air. According to the manufacturer, a German company called Green City Solutions, each of these "City Trees" can remove the same amount of pollution as 275 typical trees.

The project in Place de la Nation is a pilot, but if it is successful, Green City Solutions could roll out the "trees" across Paris. But this technology does not come cheaply; each City Tree costs more than $25,000.

Paris will also benefit from the more old-fashioned trees. Compared with other global cities, Paris only has a moderate ROI of tree planting. The central parts of Paris are the densest and have the highest estimated ROI. For an additional annual investment of $10 million in tree planting and maintenance, we estimate that 2.3 million people could have a reduction of > 1 µg/m³ of $PM_{2.5}$.

Results from the Paris study



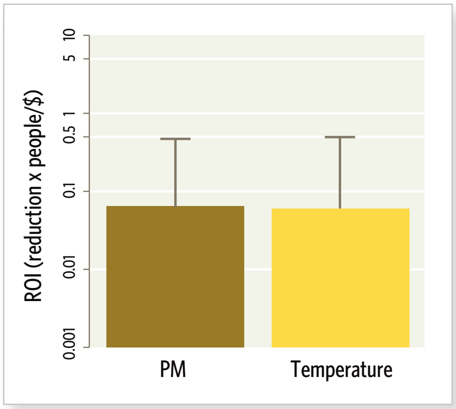


Figure 30. ROI for tree planting for Paris.

PM ROI

Higher Return ▇ ▇ ▇ ▇ Lower Return

Map 25. Neighborhood-level ROI for Paris (PM reduction).

Investment	Annual Cost ($)	> 1 ug/m² $PM_{2.5}$	1.5 deg C
10% of sites	10,300,000	2,350,000	2,360,000
20% of sites	19,900,000	3,340,000	3,350,000
Full Investment	89,600,000	6,040,000	6,040,000

Table 18. Temperature and PM reduction benefits under three investment scenarios, for Paris.

RIO DE JANEIRO

Photo © iStock, EduLeite

For many visitors to Rio de Janeiro, one of the first stops is the Rua Cosmo Velho, where they can hop on a narrow-gauge, cog train for a 20-minute ride to the top of Corcovado. Once there, they will have a spectacular view over the city, Gaunabara Bay, and the famous beaches, as well as a close-up look at one of Rio's, and the world's, iconic images: the nearly 100-foot tall statue known in Portuguese as ***Christo Redentor***, Christ the Redeemer—the largest Art Deco statue in the world.

The visitors to Corcovado may not even notice the forest they pass through on their way to the top. That would be a shame, because the forest is a rare jewel, an example of the Mata Atlântica, the Atlantic rainforest that once covered an area twice the size of Texas along Brazil's eastern seaboard. Less than 10 percent of that rich forest ecosystem remains, including about 15 square miles surrounding Corcovado, protected since 1961 as Tijuca National Park.

The story of the creation of the park may reveal part of Rio's future as well. The forest is a re-creation rather than a remnant of the one that greeted the first Portuguese explorers. By the mid-19th century, the Atlantic Forest surrounding Rio had been cut down to make way for sugar and coffee plantations. In 1861, the Brazilian king, Dom Pedro II, realized the deforestation would affect the city's supply of drinking water. He ordered the continent's first reforestation program. In less than two decades, employees and slaves planted more than 110,000 seedlings.

Another bold reforestation effort may now be needed—this one far larger than Dom Pedro's. Rio de Janeiro will likely be severely impacted by the effects of global warming. Temperatures are expected to rise by 1° C by 2020, according to the Urban Climate Change Research Network. Brazil's National Institute of Meteorology predicts that Rio will experience an increase of 3.8 degrees Celsius by 2080.

While Rio has extensive protected areas within the municipal boundaries—and Tijuca National Park by itself it more than 10 times the size of New York's Central Park—most are at the edges of the city with few entrances and distant from the central cores. Most Cariocas, as the residents of Rio are known, see relatively few trees on a daily basis unless they are fortunate enough to live in the wealthier neighborhoods near the Ipanema and Copacabana beaches.

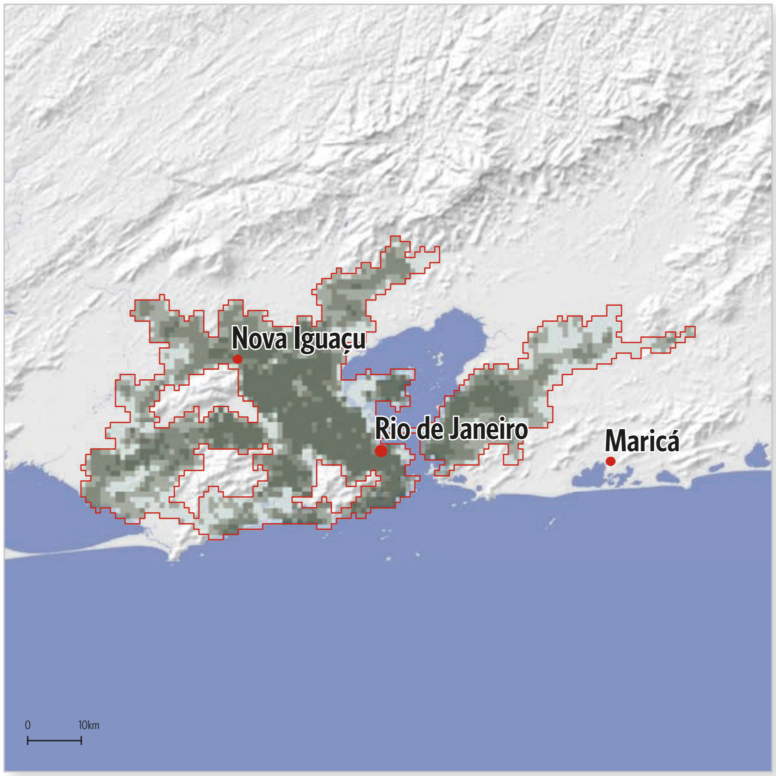
That distinction highlights another challenge for Rio. In most cities, the urban heat island effect is most pronounced in the city centers. In Rio, however, people living in the working-class neighborhoods on the outskirts of the city and the densely populated slums called *favelas* experience the most intense effects of urban heat islands. According to a study conducted in 2000, the Bangu neighborhood, some 20 miles northwest of Copacabana, is the hottest in the city, while the richer areas of the South Zone and Barra da Tijuca are the coolest.

Rio has been working to reforest its hillsides for decades. Beginning in 1986, the city's Environmental Secretariat led a community reforestation program and planted over 6 million seedlings on 2,200 hectares of land within the city limits. Once Rio won the right to host the 2016 Summer Olympics, the tree-planting effort accelerated. In 2012, authorities in Rio promised to plant 24 million trees (later increased to 34 million) by the end of 2015 in order to mitigate greenhouse gas emissions from the Olympic Games and to provide other benefits.

Unfortunately, only a fraction of the promised trees have been planted. The priority now is to make a full inventory of trees in the city, a two-year effort to determine the size, condition, and classification of every tree in the city, with the data feeding into Rio's Greenhouse Gas Inventory.

Compared with other cities globally, Rio has moderate ROI from tree planting. The neighborhoods with the highest estimated ROI are downtown Rio and the southern portion of Duque de Caxias considered in our report. For an additional annual investment of $2.4 million in street trees, we estimate that more than 900,000 people could have a reduction of 1.5° C (2.7° F) in summertime air temperature.

Results from the Rio de Janeiro study



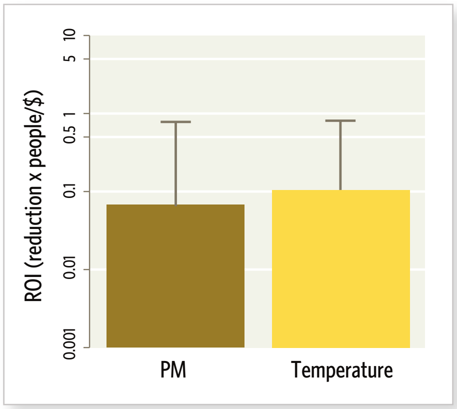


Figure 31. ROI for tree planting for Rio de Janeiro.

PM ROI

▨ ▨ ▨ ▨

Higher Return Lower Return

Map 26. Neighborhood-level ROI for Rio de Janeiro (temperature reduction).

Investment	Annual Cost ($)	> 1 ug/m^2 PM$_{2.5}$	1.5 deg C
10% of sites	2,380,000	912,000	942,000
20% of sites	4,800,000	1,450,000	1,540,000
Full Investment	17,700,000	1,950,000	2,590,000

Table 19. Temperature and PM reduction benefits under three investment scenarios for Rio de Janeiro.

Photo © © iStock, EduLeite

SEOUL

It is a rite of spring in Seoul, as familiar—and nearly as ancient—as the cherry blossoms. But the arrival of "Hwang Sa" is not nearly so benevolent a harbinger of the season. "Hwang Sa," or Yellow Dust, originates in deserts and is carried into the atmosphere by strong winds and onto the Korean Peninsula via the jet stream. Millennia ago—the earliest record of Hwang Sa in Korea is from the Second Century AD—the dust brought little more than a passing inconvenience. In the industrial era, however, the sands bring with them pollutants from both local and distant sources..

Small wonder that East Asia's concentrations of $PM_{2.5}$ are the highest in the world, according to World Health Organization rankings. South Korea depends heavily on coal for electricity; in South Korea about 50 coal plants generate electricity, a dozen more are planned by 2021, and the reliance is expected to deepen. According to government plans, most of the increasing demand for electricity in the coming years will be met with new coal and gas plants. Diesel fuel for cars and trucks further contribute to local pollution.

A joint U.S.-Korea study, one of the most intensive air-quality investigations ever, will help clarify the sources of pollution. Known as KORUS-AQ, the study involves more than 580 researchers from 72 institutions, including NASA. Three planes, two ships, and 300 ground-based monitoring sites combine to take air samples from across the Korean peninsula. NASA, for example, flies a DC-8 plane outfitted with sophisticated sensors at low altitudes up and down the length of the Yellow Sea, over rural areas, and straight through crowded downtown Seoul, sometimes flying as low as 1,000 feet.

Whatever the source, pollution in Seoul remains a stubborn problem. South Korea falls short of the WHO standard of 10 micrograms/m^3 for average exposure to $PM_{2.5}$, with average exposure nearly double safe levels. In 2015, the air quality in Seoul over a 24-hour period averaged "unhealthy for sensitive groups" or worse on 53 days. For comparison, Los Angeles counted only seven days in that category, while New York did not have a single day with air quality in that "unhealthy" range. According to researchers at Yale, in April, 2016, Koreans suffered through high levels of $PM_{2.5}$ half of all days.

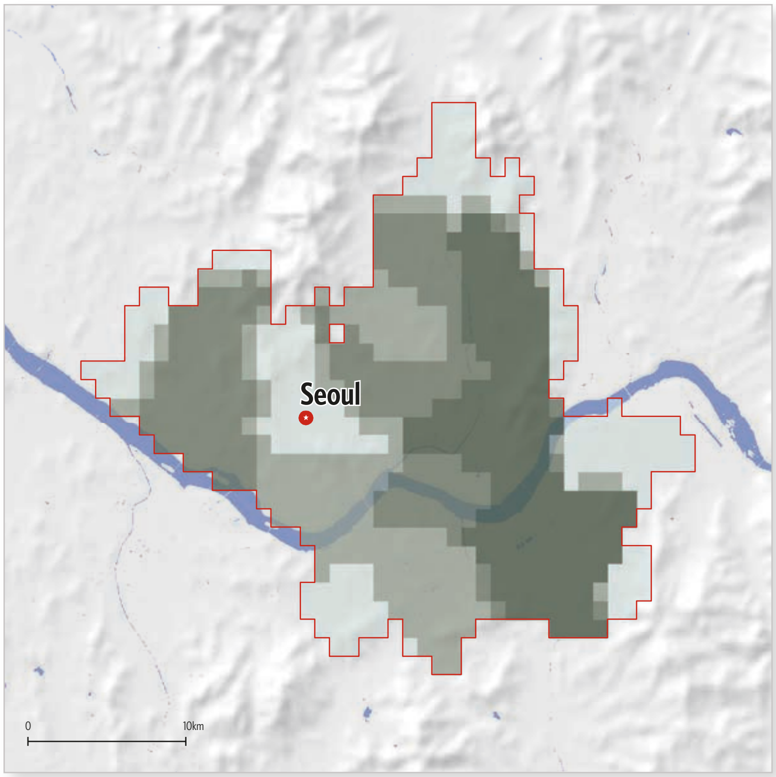
South Korea has implemented a range of policies and management efforts to address air pollution for more than three decades. South Korea promulgated its first regulation on air quality in 1993, the country's first PM_{10} standard in 1995, and further legislation for Seoul in 2003.

Government officials in 2016 said they were considering closing coal-fired power plants that were more than 40 years old in a move to tackle the pollution problem.

To address emissions in the public transportation sector, compressed natural gas buses are being introduced in Seoul and other cities, with the number increasing from just 74 in 2001 to 23,000 in 2010. The Bus Rapid Transit System was also established to create bus lanes in the center of roads for more efficient traffic flows, and congestion fees are collected at specific tunnels.

Seoul is also looking to increase greenspace in the city, setting a goal of more than 800,000 acres by 2020. Our results suggest that tree planting could also have temperature-mitigation benefits. Compared with other global cities, Seoul has a fairly high ROI of tree planting, with the highest ROI in a north-south band running through the center portion of the city. We estimate that an additional annual investment of $1.9 million in street tree planting could give more than 600,000 people a reduction of 1.5° C (2.7° F).

Results from the Seoul study



PM ROI

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Higher Return Lower Return

Map 27. Neighborhood-level ROI for Seoul (temperature reduction).

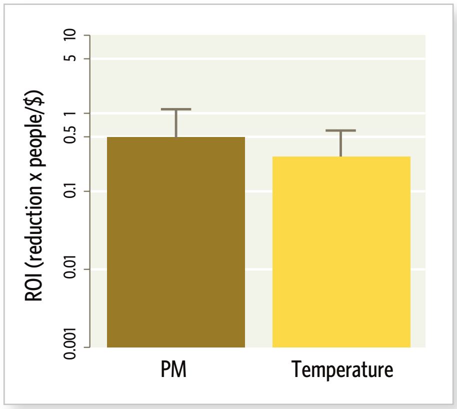


Figure 32. ROI for tree planting for Seoul.

Investment	Annual Cost ($)	> 1 ug/m^2 PM$_{2.5}$*	1.5 deg C
10% of sites	1,910,000	646,000	647,000
20% of sites	4,050,000	1,210,000	1,200,000
Full Investment	20,300,000	3,590,000	3,590,000

*Note: Most people will receive a reduction of > 10 ug/m^2 PM$_{2.5}$ in this city

Table 20. Temperature and PM reduction benefits under three investment scenarios for Seoul.

Photo © chuyu

SHANGHAI

In 2013, temperatures in Shanghai topped 38° C (100° F) for 10 straight days, making it the hottest July in 140 years. The city's Xujiahui weather observatory recorded a temperature higher than 41° C (105° F), an all-time record, on July 26. The evening brought no relief from the heat. Temperatures dropped only into the high 80s, some 10 degrees above normal.

The heat wave made headlines around the world, but it is unlikely to be the last such event for two reasons. The first is global: The long-term rise in average temperatures may cause changes in weather patterns, such as a shift in the jet stream, that may increase temperatures in and around Shanghai, as well as changes the frequency and intensity of the monsoon.

The second reason to expect more heat weaves in Shanghai is because of its success: The city has been booming for decades, and the population now tops 20 million. And Shanghai continues to grow: Since 1984, the area of urbanized land in Shanghai increased more than three times, at an annual rate of nearly 11 percent. According to one study, between 1997 and 2008 alone, developed land in Shanghai more than doubled, mostly as a result of converting cropland and forest to urban use.

In response, Shanghai made a concerted effort to increase green spaces in the city. The United Nations estimates that the city doubled the amount of green spaces between 2000 and 2008. As part of its green spaces expansion, a number of parks have been established in Shanghai's urban areas.

The city has also undertaken a massive effort to increase the amount of green walls and rooftop gardens in the city. New rules introduced in October 2015 mandate that at least 50 percent of the roof area of all new buildings must be covered in plants. Shanghai plans to plant 400,000 square meters of rooftop gardens in 2016 alone. By 2020, 2 million square meters of greenery will likely be added to the roofs and walls of Shanghai's buildings.

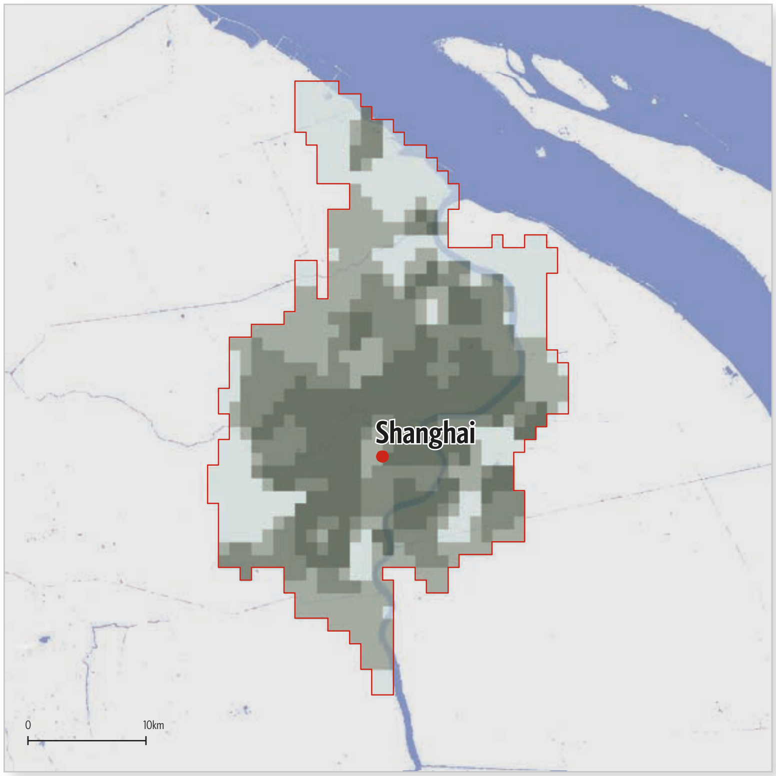
More green roofs by themselves will not be enough. As a relatively high-density city, Shanghai also has a high estimated ROI of tree planting for temperature mitigation. Generally, the neighborhoods with the highest ROI are in the denser central portions of the city. For an annual additional cost of $1.6 million, almost 2 million people could have a reduction of summertime temperatures of 1.5° C (2.7° F).

Shanghai is trying to change course on a broader scale, improving transportation and moving to an economic model based less on land-hungry industry and more on banking and information technology. By 2020, the city government plans to extend Shanghai's metro, already the world's longest, to more than 800 kilometers. In July 2010, the central government announced plans for a Shanghai-Nanjing high-speed rail route. The new route is expected to cut journey time between the two cities from two hours to just 72 minutes, and has the potential to ease traffic congestion if commuters opt for the new train rather than their cars.

The city is also reducing its dependence on coal. Under the 2013 Clean Air Action Plan, the city will ban the burning of coal by 2017, which means shutting or upgrading thousands of coal-fired boilers and furnaces.

Meeting Shanghai's growing energy demands without coal and while preserving open space will require a large-scale shift to renewable sources. China built the world's first large-scale offshore wind farm in Asia near the East China Sea Bridge, a 20-mile crossing that links Shanghai with the Yangshan Deep Water Port.

Results from the Shanghai study



Map 28. Neighborhood-level ROI for Shanghai (temperature reduction).

PM ROI

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Higher Return Lower Return

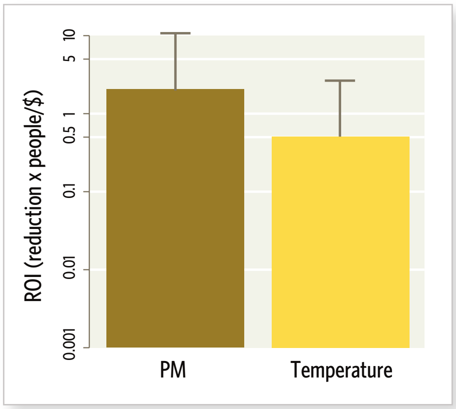

Figure 33. ROI for tree planting for Shanghai.

Investment	Annual Cost ($)	> 1 ug/m^2 PM$_{2.5}$*	1.5 deg C
10% of sites	1,610,000	1,980,000	1,980,000
20% of sites	3,230,000	3,140,000	3,140,000
Full Investment	16,200,000	6,800,000	6,800,000

*Note: Most people will receive a reduction of > 10 ug/m^2 PM$_{2.5}$ in this city

Table 21. Temperature and PM reduction benefits under three investment scenarios for Shanghai.

Chapter 6

Photo © iStock, visualspace

Barriers to Using Nature as a Solution

We hope our analyses will go some way toward closing the knowledge gap about the value of a natural infrastructure approach to keeping air healthy. But we also recognize that significant barriers remain to reaching nature's full potential. In this section, we outline three important barriers to increased tree planting, and discuss how some cities are overcoming them.

Financial barriers

In the report, we presented the case for thinking of urban forests as vital green infrastructure, that can help make air cleaner and cooler. However, the term "green infrastructure" also captures a reality: planting and maintaining trees in an urban environment costs money. Trees along streets or otherwise in the public right of way are generally paid for by governments, which may struggle to find enough money to fund maintenance of existing trees, let alone the planting of new ones.[100] One report suggests in the United States that around 75 percent of dollars for urban forestry goes toward maintenance and management, with only around 14 percent reserved for planting.[101] Perhaps more problematic is that the absolute size of the budget for urban forestry is tiny: The average large cities in the United States (population > 100,000) spend around $5 per person per year, around 0.3 percent of the average municipal budget in these cities.

One of our goals in writing this report is to convince decision-makers that urban forestry can be thought of as, in part, an investment in health. Public health budgets, of course, are also stretched in many cities and countries, and we are not calling for raiding those budgets to provide for more tree planting. Rather, we simply note that current health expenditures is (appropriately) a much larger budgetary priority than urban tree planting. In the United States, total expenditures on health care was roughly $3.0 trillion in 2014, or roughly $9,500 per person. Around a quarter (28 percent) of this spending was by the federal government, with state and local governments accounting for an additional 17 percent of spending.[102] If, as this report has shown, there are health benefits to tree planting, then what is a modest 0.1 percent increase in health spending—say, an extra $5 or $10 per person per year—would double or triple urban forestry budgets in most U.S. cities.

There are, of course, many other creative financing mechanisms that cities use to fund trees.[100] Among these:

- Parcel taxes or landscaping districts—Individual property owners benefit from having street trees nearby, in a really quantitative way, with assessed property values increasing significantly when cities provide trees. The idea behind a parcel tax then is to treat trees as infrastructure to provide to citizens, just as some cities charge parcel taxes or other fees for stormwater or other public infrastructure.

- Green area ratio or tree-cover requirements—Some cities require new developments to maintain a certain level of tree cover. In the simplest case, tree-protection ordinances require existing trees to be retained during development, if possible. Other cities require a certain amount of tree cover in new developments, but allow developers to choose how to hit that target. More generally, cities could choose to adopt a Green Area Ratio (GAR), allowing certain kinds of land cover to count as green (tree cover, but also green roofs, green infrastructure for stormwater mitigation, etc.) and requiring a certain ratio of green elements to total parcel area, with the ratio usually varying by the site's zoning.

- Bonds—In developed countries, particularly the United States, it is common for cities to issue general obligation bonds to fund new infrastructure (although not generally maintenance). These have occasionally been used to finance tree planting.

- General funds—Most often, cities finance urban forestry out of general revenue. There is intense competition for this general revenue, though, which limits how much cities can put toward trees.

- Government and private foundation grants—Some cities have turned to one-time grants to finance tree planting. One challenge with this funding stream is ensuring there is enough money for maintenance over time.

Institutional barriers

Different government agencies often have very different missions, and so have different visions about what should be done (Photo 5). What benefits one agency or actor may impose a cost on another. A tree-planting program might benefit an electric utility but impose costs on the parks department. Or a city's tree protection ordinance might conflict with the desire of urban planners for dense, walkable neighborhoods. Many cities struggle to harmonize the goals and actions of different agencies. For instance, a stormwater management agency and an electric utility may both love the idea of tree planting and natural infrastructure, but differ wildly in where and how they want to plant trees.[13]

Photo © iStock, Adam Korzekwa

Photo 5. City governments have the power to improve their residents' health with better coordination and investment in tree planting. (City of Philadelphia).

For the purposes of this report, the most important institutional barrier is simply that the agency in most cities that manages trees (e.g., the parks and recreation department) does not have health benefits in its mandate. Most of its employees may not be used to thinking about the air-quality benefits of trees, or view their provision as part of their job. Conversely, public health officials think a great deal about air quality, often from the perspective of regulations on emissions, or about the risk heat waves pose (where there is a well-defined process of heat health action plans, see next section). But they may not consider trees as a potential partial health solution, or view tree planting as part of their mandate. That means that in many municipal planning processes, there is no one speaking up for the potential health benefits of trees.

A broad, inclusive set of stakeholders involved in the creation of an urban-forestry plan can often help. Several reports list best practices for creating urban-forestry plans, and often one of the first recommendations is having a broad set of stakeholders involved. For instance, the United States Forest Service[103] recommends including all of the "key players" involved, including the parks department, utilities (gas, electric, and cable), town planners, mayor or town council members, and non-governmental organizations dedicated to trees. To this list, we would suggest adding a public health official.

Another good place to bring health benefits into urban forestry is during the comprehensive plans of sustainability plans. While not all cities do these, they are a powerful way to make sure all the agencies in a city agency are pulling toward a coherent vision of a better city and supporting one another's efforts. Because the planning frame is larger than one narrow issue (urban forestry), such broad plans can be a good place to make linkages between the actions of different departments.[104]

Collective action barriers

If cities want to go beyond working in the public right of way and instead encourage tree planting on the (usually much larger) private land base, they face a collective action problem. The largest challenge is getting thousands of private land owners to participate in a tree-planting program. This is a form of a collective action problem, which occurs for many types of natural infrastructure, but it is a particularly thorny challenge for tree-planting campaigns because of the small parcels of most urban landowners, which necessitate influencing the decisions of thousands. Cities often launch broad public education campaigns to win citizens' support for tree planting. They also will interact with community groups and neighborhoods institutions that can help win buy-in from many property owners at once.[13]

Another major tool is regulatory programs that mandate certain tree-protection or planting actions by landowners. For instance, many towns have tree-protection ordinances, which mandate the protection of large or valuable trees where possible. The related ordinance for new developments are planting requirements, which essentially require that a certain number or area of trees be present on a parcel. Because tree planting or maintenance is not always desirable or possible on every parcel (e.g., a tall build in the center part of a city), there is a concept of "tree banking," essentially allowing development that violates tree ordinances if an equivalent number or area of trees are planted elsewhere in the city. The report *Guidelines for Developing and Evaluating Tree Protection Ordinances* has a list of common ordinances and a discussion of their pros and cons.[105]

Related to the idea of tree banking is the creation of financial incentives for tree planting that landowners can respond to if they wish. In some cities, the link between the shade trees provide and the benefits in terms of reduced electricity used have encouraged utilities to make this link tangible with utility bill donations or incentives. For instance, a utility may provide tree saplings to property owners and agree to reduce electric bills by a certain amount if trees are planted. The owners must agree in return to maintain the trees. Trees are often positioned on the western edge of a house, to provide maximum shade during the hot afternoon. Having shade trees around a house makes it more attractive, and these aesthetic benefits add tangible value when a home is resold. But more importantly for the utility, the trees reduce the house's electrical use, particularly on summer afternoons when the air conditioning is running strong.

Chapter 7

Photo © Siephoto / Masterfile

Heat Action Planning

For more than 10 years, the C40 Cities Climate Leadership Group (C40) has been a critical driver of climate action in the world's largest and most influential cities.

C40's network of more than 85 cities – representing more than 650 million people around the world and one quarter of the global economy – are committed to tackling climate change and driving urban action that reduces greenhouse gas emissions and climate risks. C40 helps cities identify, develop and implement local policies and programmes that have collective global impact, while increasing the health, wellbeing and economic opportunities of urban citizens.

Working across multiple sectors and initiative areas, C40 empowers cities to connect with each other and share common goals and challenges, providing a suite of services in support of their efforts: direct technical assistance; facilitation of peer-to-peer exchange; research, knowledge management, city diplomacy, and communications. C40 understands that cities are a leading force for climate action around the world and positions them as such, defining and amplifying their call to national governments for greater support and autonomy in creating a sustainable future.

One way that cities are trying to address the challenge of excess heat is through heat action planning. C40 Cities Climate Leadership Group and Global Cool Cities Alliance (GCCA) formed a network of cities called the Cool Cities Network (CCN). This network is comprises of more than 14 leading cities from all over the world that face the impacts of extreme heat and work together to develop, share, and replicate best practices to address the issue.

The global cities in the C40 network are taking action to help minimize the impact of extreme heat on their citizens. These actions can be classified into two broad categories: 1) heat emergency response measures, and 2) built environment heat mitigation and adaptation measures. Heat emergency response measures aim to address the threat of extreme heat events by executing emergency response plans that aim to minimize impacts of heat waves on citizens and particularly vulnerable communities. In addition, heat mitigation and adaptation measures focused on the built environment work to "cool" cities by incorporating cooling mechanisms in the structure of the city.

Heat emergency response measures

Preparing for an emergency heat event is a manifold process. It requires numerous components of the emergency-response plan to work in tandem, including unified actions from city agencies and departments. One of the most crucial parts of response planning is community mobilization and ensuring that the communications planned to reach the public are both flexible and clear to account for any unforeseen delays in the response. Cities like Toronto and Washington, D.C., have proactively developed heat emergency-response plans, which allow the cities to implement measures in an effective and timely manner, ensuring minimal impact of a heat wave on citizens.

Tokyo, Japan, has adopted several innovative cooling measures to provide the citizens solace from extreme heat. In order to identify the most vulnerable areas, the city conducted a heat-mapping exercise. The city was divided into 500-meter grids and priority areas were identified. One of the measures implemented in the city is "Dry Mist." Sensor-controlled nozzles help in refreshing the people on the road by spraying dry mist. The sensors spray water, which evaporates as soon as it comes in contact with the atmosphere. This ensures that people do not get wet. However, the latent heat of evaporation creates a cooling effect. Another cooling measure adopted by Tokyo is actually an age-old Japanese tradition for summer called "Uchimizu." This is a water-sprinkling practice in which people used to sprinkle water on streets during summer months to keep the area cool. Tokyo has adopted a greener version of "Uchimizu" that uses rainwater to sprinkle on the roads, keeping them cool during extreme heat days.[106]

Washington, D.C., also launched a Heat Emergency Plan. The plan has a strong focus on the vulnerable population and aims to provide them with information about the heat wave by highlighting the cooling spots across the city where citizens can take refuge. Citizens are also notified of a heat warning based on the heat index—a combination of heat and humidity. The cooling centers are made open to the public as soon as an extreme heat warning is issued in the city. The District has also set in place a strong response system through the District Response Plan for emergency heat situations, which comprises of multiple stakeholders responsible for its effective implementation. The District Office of Unified Communication is held responsible for communicating information about the heat warning to the public in a successful manner.

Built environment heat mitigation and adaptation measures

Built environment and the "urban heat island effect"—which is caused by infrastructure—are key characteristics of our cities today. As the global temperatures rise, the frequency and intensity of extreme weather events, including extreme heat, is increasing dramatically. Therefore, it is imperative to adapt to these changes in order to ensure good quality of life for the citizens. Cities like New York, Tokyo, Paris and many more are implementing several long-term measures that would modify the built environment in a way that it is much more resilient to extreme heat. They have incorporated various cooling measures in the city.

New York, New York, launched its NYC CoolRoofs Program in 2009 as a "Cool it Yourself" program encouraging building owners to paint their rooftops white. The Mayor's office of New York City supported the program by coordinating a corps of volunteers and later evolved the program as a job-training initiative. The program has successfully coated more than 6 million square feet of rooftops to date and have engaged local property owners, community partners, workforce training organizations, and volunteers throughout the process. Every 2,500 square feet of rooftop that is coated can reduce the city's carbon footprint by one ton of CO_2.

Los Angeles, launched its Cool Roof Ordinance in 2014 in an update of its Green Building Code. The law requires all residential roofing material to meet a minimum "aged solar reflectance" (solar reflectance of roof after aging) and "thermal emittance" criteria (exceptions apply). The ordinance also has an incentive program, providing rebates to owners of single-family and multifamily household properties.

Tokyo, Japan, is installing thermal-barrier coating and water-retentive pavement in the city as a part of road maintenance and construction within central Tokyo, using the opportunity of the 2020 Summer Olympics to renovate city pavements, in and around the Olympic venues. The city has so far installed 84 kilometers of cool pavements including 19 kilometers of water-retentive pavement and 65 kilometers of thermal barrier coating pavement. The Tokyo Metropolitan Government has set a target of 136 kilometers of these innovative pavements by 2020, through adding 10 kilometers every year.

Athens, Greece, has been strongly promoting the construction of green roofs. The city has recently completed construction of green roofs on 13 primary and kindergarten schools. The project aims to increase awareness among students, provide insulation and, in particular, cooling benefits during hot weather, reduce energy usage, increase storm-water management, and improve aesthetics of the buildings.[107]

Paris, France, started an initiative called "Des jardins sur les murs" or "Garden on the walls" when more than 21,000 Parisians voted the initiative through the citizen referendum of the Participatory budget in 2014. As a part of the initiative, Paris plans to develop 41 green walls in the city. Green walls are not a new concept for Paris; in fact, from 2001 to 2013, the city planted 118 walls.[108] Paris has committed to building 100 hectares of green walls and roofs by 2020, including the 41 green walls. One-third of this area will be dedicated to urban agriculture.[109]

As major cities globally are experiencing increasing "urban heat island effect" and more extreme heat events because of global warming and changing weather patterns, addressing these hazards by adopting cooling techniques and strategies is an important way for cities to adapt to climate change while reducing greenhouse gas emissions that drive global—and local—temperature increases.

By 2050, 250,000 people

could die each year because of urban heat, unless cities take proactive steps to adapt to global warming.

Photo © iStock, Allija

Chapter 8

Photo © Aaron Coury

Conclusions

We are entering the urban era. By 2050, the vast majority of humanity will live in cities. One of the preeminent tasks of cities will be making themselves vibrant, healthy, attractive places to live. This report has focused on just one small part of this task, the quest to make urban air healthier. Cities continue to strive to reduce concentrations of particulate matter and other atmospheric pollutants. And they are beginning to plan for the increased frequency and intensity of heat waves that climate change will likely bring. Succeeding against these twin challenges—air pollution and excess heat—will require an array of approaches. In this report, The Nature Conservancy has tried to understand—working in coordination with C40—whether nature can play a role in helping solve these twin challenges.

Perhaps it is easiest to summarize our results relative to the main questions we set out to answer in this report:

Which cities and neighborhoods can natural infrastructure help the most? Our results stressed the importance of targeting, at multiple scales. The benefits that trees provide are localized, generally within a few hundred meters of the planting. We recommend, therefore, that trees not be described as a way to clean up and cool an entire city's airshed. Rather, tree planting is a targeted tool that can be used to provide benefits to specific people in specific places. Locations with a high ROI of tree planting have, among other things, a high number of people that live near the planting and can benefit from it. We have tried to list in more detail in the body of the report planting guidelines that cities can use to ensure they are targeting their tree-planting efforts appropriately, to maximally deliver benefits to their citizens.

Where is natural infrastructure a cost-effective investment, relative to common built infrastructure alternatives? We find that street trees are a cost-competitive strategy for reducing particulate matter concentrations and temperature mitigation. The benefits that trees deliver, in terms of $/ton of PM removed or $/degree of temperature mitigation, are in the same range as major built infrastructure alternatives. More importantly, street trees are able to deliver benefits both to PM and temperature mitigation, while grey infrastructure alternatives generally are not.

How much vegetation is enough? We did not find one single level of investment that is "enough." Rather, tree planting for healthy air is an investment, and like any investment has a curve of potential payoffs. Many cities currently have relatively modest investment in urban forestry, and we find that air-quality benefits suggest a significant increase in investment is warranted. However, where cities end up along this investment curve is a choice they will have to make, based upon their budget and their priorities.

How much investment, in dollar terms, is needed? Again, there was no clear single level of investment that is needed. However, we were able to show that even a relatively modest additional annual global investment of $100 million for tree planting and maintenance, targeted toward the cities and neighborhoods where it would deliver the most benefits, could help improve the lives of millions.

What fraction of the air-quality problem can vegetation solve? Street trees have the potential to solve a modest portion of the air-quality problem. While the environmental community needs some humility, since the scope for nature-based solutions is modest relative to the scale of the global challenge, there are still millions of people who can be cost-effectively helped by street trees.

In conclusion, tree planting constitutes a part of a cost-effective portfolio of interventions aimed at controlling particulate matter pollution and mitigating high temperatures in cities. While trees cannot and should not replace other strategies to make air healthier, trees can be used in conjunction with these other strategies to help clean and cool the air. Moreover, trees provide a multitude of other benefits beyond healthier air. In the right spot, trees can both help make our air healthier and our cities more verdant and livable. They are an important way that we can make our coming urban world—the cities in which most of us will live—resilient, livable, and thriving.

Appendix I

Photo © Devan King

Appendix 1: City Rankings

This table lists the median return on investment (ROI) of tree planting for both temperature and particulate matter reduction. The units are the physical reduction (e.g.,°C for temperature) multiplied by the population receiving that reduction, divided by the cost in US2015$. The three scenarios of impact (High, Medium, and Low) show the uncertainty in how effective trees are at providing this service. Note the median ROI figure for a city means, by definition, that half of the neighborhoods have a higher ROI and half the neighborhoods have a lower ROI. The variance within cities is often quite large, so even cities that have a low median ROI often have neighborhoods with relatively high ROI. We urge interested readers to consult our website nature.org/healthyair, which has detailed information for all cities considered in the report. Note that we examined broad metropolitan regions; for instance, we examined Washington, D.C., plus surrounding towns in the states of Virginia and Maryland.

	ROI for temperature (°C x population/$)			ROI for PM (°g/m^3 x population/$)		
City	**High**	**Medium**	**Low**	**High**	**Medium**	**Low**
Abidjan	0.74	0.52	0.31	1.42	0.91	0.44
Accra	0.93	0.66	0.39	2.08	1.33	0.64
Addis Ababa	0.43	0.30	0.18	0.54	0.34	0.17
Ahmadabad	0.99	0.70	0.41	4.18	2.67	1.28
Algiers	0.35	0.25	0.15	0.35	0.22	0.11
Al-Iskandariyah (Alexandria)	0.95	0.67	0.40	2.28	1.45	0.70
Al-Khartum (Khartoum)	0.11	0.08	0.04	0.48	0.31	0.15
Al-Qahirah (Cairo)	0.81	0.57	0.34	3.63	2.32	1.11
Amman	0.11	0.08	0.05	0.26	0.16	0.08
Amsterdam	0.05	0.04	0.02	0.06	0.04	0.02
Ankara	0.10	0.07	0.04	0.17	0.11	0.05
Antananarivo	0.67	0.47	0.28	0.14	0.09	0.04
Ashgabat	0.32	0.23	0.13	0.67	0.43	0.21
Asuncion	0.26	0.18	0.11	0.17	0.11	0.05
Athens	0.13	0.09	0.05	0.20	0.13	0.06
Atlanta, GA	0.01	0.01	0.01	0.01	0.01	0.00
Austin, TX	0.01	0.01	0.00	0.01	0.00	0.00
Baghdad	0.21	0.15	0.09	1.08	0.69	0.33
Baku	0.19	0.13	0.08	0.37	0.24	0.11
Baltimore, MD	0.04	0.02	0.01	0.03	0.02	0.01
Bamako	0.59	0.41	0.24	0.91	0.58	0.28
Bangalore	0.45	0.32	0.19	0.89	0.57	0.27
Bangui	0.03	0.02	0.01	0.03	0.02	0.01
Barcelona	0.41	0.29	0.17	0.47	0.30	0.15
Beijing	0.40	0.28	0.16	2.95	1.88	0.90
Beirut	0.34	0.24	0.14	0.84	0.54	0.26
Belgrade	0.12	0.09	0.05	0.17	0.11	0.05
Belo Horizonte	0.24	0.17	0.10	0.13	0.08	0.04
Berlin	0.08	0.05	0.03	0.09	0.06	0.03
Birmingham, AL	0.00	0.00	0.00	0.00	0.00	0.00
Bishkek	0.01	0.01	0.00	0.01	0.01	0.00

ROI of PM and Temperature Reduction

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Higher Lower

	ROI for temperature (°C x population/$)			ROI for PM (°g/m^3 x population/$)		
City	High	Medium	Low	High	Medium	Low
Bissau	0.47	0.33	0.19	0.86	0.55	0.26
Bogotá	0.23	0.17	0.10	0.10	0.06	0.03
Boston, MA	0.02	0.01	0.01	0.01	0.01	0.00
BrasÍlia	0.02	0.02	0.01	0.01	0.01	0.00
Bratislava	0.05	0.04	0.02	0.07	0.05	0.02
Brazzaville	0.73	0.52	0.30	0.40	0.26	0.12
Bridgeport, CA	0.01	0.01	0.00	0.01	0.00	0.00
Brussels	0.04	0.03	0.02	0.05	0.03	0.02
Bucharest	0.32	0.23	0.13	0.51	0.32	0.15
Budapest	0.08	0.06	0.03	0.12	0.08	0.04
Buenos Aires	0.21	0.15	0.09	0.14	0.09	0.04
Bujumbura	0.32	0.23	0.13	0.36	0.23	0.11
Busan	0.25	0.17	0.10	0.33	0.21	0.10
Campinas	0.14	0.10	0.06	0.12	0.08	0.04
Canberra	0.02	0.01	0.01	0.01	0.00	0.00
Cape Town	0.13	0.09	0.05	0.06	0.04	0.02
Caracas	0.18	0.13	0.07	0.08	0.05	0.02
Casablanca	0.52	0.37	0.22	0.38	0.24	0.12
Changchun	0.18	0.13	0.07	0.48	0.31	0.15
Changsha, Hunan	0.55	0.39	0.23	2.72	1.74	0.83
Chengdu	0.40	0.28	0.17	2.54	1.62	0.78
Chennai (Madras)	0.79	0.56	0.33	1.79	1.14	0.55
Chicago, IL	0.02	0.02	0.01	0.02	0.01	0.01
Chittagong	0.71	0.50	0.30	0.98	0.63	0.30
Chongqing	0.58	0.41	0.24	3.17	2.02	0.97
Colombo	0.31	0.22	0.13	0.54	0.35	0.17
Conakry	0.37	0.26	0.15	0.82	0.52	0.25
Copenhagen	0.03	0.02	0.01	0.03	0.02	0.01
Curitiba	0.13	0.09	0.05	0.09	0.06	0.03
Dakar	1.15	0.82	0.48	4.65	2.97	1.43
Dalian	0.10	0.07	0.04	0.35	0.22	0.11
Dallas, TX	0.01	0.01	0.00	0.01	0.00	0.00
Damascus	1.26	0.89	0.52	3.38	2.16	1.04
Dar es Salaam	1.10	0.78	0.46	0.74	0.47	0.23
Delhi	0.88	0.62	0.36	6.65	4.24	2.04
Denver, CO	0.00	0.00	0.00	0.00	0.00	0.00
Detroit, MI	0.02	0.01	0.01	0.02	0.01	0.01
Dhaka	3.24	2.29	1.34	10.42	6.65	3.19
Doha	0.01	0.01	0.00	0.07	0.04	0.02
Dongguan (Guangdong province)	0.40	0.28	0.17	1.94	1.24	0.59
Dublin	0.05	0.03	0.02	0.02	0.02	0.01
Durban	0.09	0.06	0.04	0.06	0.04	0.02
Faisalabad	1.15	0.81	0.48	6.19	3.95	1.90
Fortaleza	0.36	0.26	0.15	0.05	0.03	0.02
Foshan	0.24	0.17	0.10	0.78	0.49	0.24
Freetown	1.23	0.87	0.51	3.47	2.21	1.06
Fuzhou (Fujian province)	0.51	0.36	0.21	1.01	0.64	0.31
Guadalajara	0.37	0.26	0.15	0.31	0.20	0.09
Guangzhou (Guangdong province)	0.49	0.35	0.20	1.48	0.95	0.45
Guatemala City	0.32	0.23	0.13	0.16	0.10	0.05
Guiyang	0.30	0.21	0.12	0.83	0.53	0.25
Haerbin	0.31	0.22	0.13	0.58	0.37	0.18
Haikou	0.35	0.25	0.15	0.65	0.41	0.20
Hangzhou	0.38	0.27	0.16	2.08	1.32	0.64

ROI of PM and Temperature Reduction

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	ROI for temperature (°C x population/$)			ROI for PM (°g/m^3 x population/$)		
City	**High**	**Medium**	**Low**	**High**	**Medium**	**Low**
Hanoi	0.74	0.52	0.30	2.25	1.44	0.69
Harare	0.23	0.16	0.10	0.10	0.07	0.03
Havana	0.09	0.06	0.04	0.05	0.03	0.01
Hefei	0.25	0.17	0.10	1.46	0.93	0.45
Helsinki	0.02	0.01	0.01	0.01	0.01	0.00
Ho Chi Minh	1.60	1.13	0.66	1.70	1.09	0.52
Hong Kong	1.09	0.77	0.45	1.33	0.85	0.41
Houston, TX	0.01	0.01	0.00	0.01	0.00	0.00
Huhot	0.17	0.12	0.07	0.37	0.24	0.11
Hyderabad	0.53	0.37	0.22	1.48	0.94	0.45
Ibadan	0.44	0.31	0.18	0.48	0.31	0.15
Islamabad	0.12	0.08	0.05	0.45	0.28	0.14
Istanbul	0.59	0.41	0.24	0.86	0.55	0.26
Izmir	0.19	0.13	0.08	0.27	0.17	0.08
Jaipur	0.32	0.22	0.13	1.12	0.71	0.34
Jakarta	0.52	0.37	0.22	1.03	0.66	0.32
Jerusalem	0.01	0.01	0.01	0.03	0.02	0.01
Jiddah	0.02	0.01	0.01	0.08	0.05	0.03
Jinan (Shandong province)	0.36	0.25	0.15	2.53	1.61	0.77
Johannesburg	0.08	0.06	0.03	0.07	0.05	0.02
Kabul	0.85	0.60	0.35	2.37	1.51	0.73
Kampala	0.86	0.61	0.36	0.82	0.52	0.25
Kano	0.46	0.32	0.19	1.10	0.70	0.34
Kanpur	0.22	0.16	0.09	1.08	0.69	0.33
Kansas City, KS	0.00	0.00	0.00	0.00	0.00	0.00
Karachi	1.80	1.27	0.74	10.97	7.00	3.36
Kathmandu	1.58	1.12	0.66	3.98	2.54	1.22
Kigali	0.50	0.35	0.21	0.53	0.34	0.16
Kingston	0.08	0.06	0.03	0.05	0.03	0.02
Kinshasa	1.12	0.80	0.47	0.61	0.39	0.19
Kolkata (Calcutta)	0.19	0.13	0.08	0.76	0.48	0.23
Krung Thep (Bangkok)	0.44	0.31	0.18	0.79	0.51	0.24
Kuala Lumpur	0.13	0.09	0.05	0.19	0.12	0.06
Kunming	0.16	0.11	0.07	0.28	0.18	0.09
Kyiv	0.21	0.15	0.09	0.23	0.15	0.07
La Paz	0.16	0.11	0.07	0.08	0.05	0.02
Lagos	0.56	0.40	0.23	1.47	0.93	0.45
Lahore	0.37	0.26	0.15	1.97	1.25	0.60
Lanzhou	0.27	0.19	0.11	0.65	0.41	0.20
Lhasa	0.03	0.02	0.01	0.00	0.00	0.00
Libreville	0.09	0.06	0.04	0.05	0.03	0.02
Lilongwe	0.14	0.10	0.06	0.04	0.03	0.01
Lima	0.52	0.36	0.21	0.57	0.36	0.17
Lisbon	0.12	0.08	0.05	0.09	0.06	0.03
Ljubljana	0.05	0.03	0.02	0.06	0.04	0.02
Lome	0.57	0.41	0.24	1.22	0.78	0.37
London	0.07	0.05	0.03	0.06	0.04	0.02
Los Angeles, CA	0.03	0.02	0.01	0.03	0.02	0.01
Louisville, KY	0.01	0.00	0.00	0.00	0.00	0.00
Luanda	0.59	0.42	0.25	0.40	0.25	0.12
Lucknow	0.25	0.18	0.10	1.41	0.90	0.43
Madrid	0.13	0.09	0.06	0.13	0.08	0.04
Managua	0.29	0.20	0.12	0.16	0.10	0.05
Manila	0.46	0.32	0.19	0.42	0.27	0.13

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	ROI for temperature (°C x population/$)			ROI for PM (°g/m^{3} x population/$)		
City	**High**	**Medium**	**Low**	**High**	**Medium**	**Low**
Maputo	0.56	0.39	0.23	0.40	0.25	0.12
MedellÍn	0.32	0.23	0.13	0.12	0.07	0.04
Melbourne	0.03	0.02	0.01	0.01	0.01	0.00
Mexico City	0.40	0.28	0.17	0.53	0.34	0.16
Miami, FL	0.02	0.02	0.01	0.01	0.01	0.00
Minneapolis, MN	0.02	0.01	0.01	0.02	0.01	0.00
Minsk	0.35	0.25	0.14	0.43	0.27	0.13
Mogadishu	0.53	0.38	0.22	0.44	0.28	0.13
Monrovia	0.02	0.01	0.01	0.03	0.02	0.01
Monterrey	0.24	0.17	0.10	0.22	0.14	0.07
Montevideo	0.18	0.13	0.07	0.14	0.09	0.04
Montréal	0.04	0.03	0.02	0.02	0.01	0.01
Moskva (Moscow)	0.10	0.07	0.04	0.10	0.07	0.03
Mumbai (Bombay)	1.89	1.34	0.78	5.06	3.23	1.55
Nagoya	0.17	0.12	0.07	0.25	0.16	0.08
Nairobi	0.47	0.34	0.20	0.24	0.15	0.07
Nanchang	0.39	0.28	0.16	1.94	1.23	0.59
Nanjing (Jiangsu province)	0.43	0.30	0.18	2.66	1.69	0.81
Nanning	0.18	0.13	0.08	0.81	0.52	0.25
Nashville, TN	0.00	0.00	0.00	0.00	0.00	0.00
New Orleans, LA	0.00	0.00	0.00	0.00	0.00	0.00
New York, NY	0.04	0.03	0.01	0.03	0.02	0.01
Ningbo	0.14	0.10	0.06	0.55	0.35	0.17
Nouakchott	0.28	0.20	0.12	1.31	0.83	0.40
Osaka-Kobe	0.14	0.10	0.06	0.17	0.11	0.05
Oslo	0.01	0.01	0.00	0.00	0.00	0.00
Ottawa	0.03	0.02	0.01	0.01	0.01	0.00
Panama	0.14	0.10	0.06	0.03	0.02	0.01
Paris	0.09	0.06	0.04	0.10	0.07	0.03
Philadelphia, PA	0.04	0.03	0.02	0.03	0.02	0.01
Phnom Penh	0.78	0.55	0.32	0.94	0.60	0.29
Phoenix, AZ	0.01	0.01	0.00	0.01	0.00	0.00
Pittsburgh, PA	0.03	0.02	0.01	0.02	0.01	0.01
Port-au-Prince	1.22	0.86	0.51	1.88	1.20	0.58
Portland, OR	0.02	0.02	0.01	0.01	0.00	0.00
Porto Alegre	0.23	0.16	0.10	0.12	0.08	0.04
Prague	0.07	0.05	0.03	0.09	0.06	0.03
Pretoria	0.09	0.06	0.04	0.07	0.04	0.02
Pune (Poona)	0.77	0.54	0.32	1.39	0.89	0.43
Qingdao	0.30	0.21	0.12	1.10	0.70	0.34
Quito	0.23	0.16	0.09	0.14	0.09	0.04
Rabat	0.53	0.38	0.22	0.62	0.39	0.19
Rangoon	1.04	0.74	0.43	1.16	0.74	0.36
Recife	0.38	0.27	0.16	0.15	0.10	0.05
Riga	0.08	0.06	0.03	0.05	0.04	0.02
Rio de Janeiro	0.15	0.11	0.06	0.11	0.07	0.03
Roma (Rome)	0.05	0.04	0.02	0.04	0.02	0.01
Sacramento, CA	0.02	0.01	0.01	0.01	0.00	0.00
Saint Petersburg	0.09	0.06	0.04	0.06	0.04	0.02
Salvador	0.66	0.47	0.27	0.20	0.13	0.06
San Diego, CA	0.01	0.01	0.01	0.01	0.01	0.00
San Francisco, CA	0.01	0.01	0.00	0.00	0.00	0.00
San Jose	0.15	0.10	0.06	0.10	0.06	0.03

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	ROI for temperature (°C x population/$)			ROI for PM (°g/m^3 x population/$)		
City	**High**	**Medium**	**Low**	**High**	**Medium**	**Low**
San Jose, CA	0.02	0.01	0.01	0.01	0.00	0.00
San Juan	0.07	0.05	0.03	0.06	0.04	0.02
San Salvador	0.26	0.18	0.11	0.22	0.14	0.07
Sanaa	1.09	0.77	0.45	3.21	2.04	0.98
Santiago	0.23	0.16	0.10	0.18	0.12	0.06
Santo Domingo	0.38	0.27	0.16	0.36	0.23	0.11
São Paulo	0.30	0.21	0.12	0.31	0.20	0.09
Sarajevo	0.03	0.02	0.01	0.03	0.02	0.01
Seattle, WA	0.02	0.01	0.01	0.01	0.00	0.00
Seoul	0.40	0.28	0.17	0.79	0.50	0.24
Shanghai	0.71	0.50	0.29	3.17	2.02	0.97
Shantou	0.29	0.20	0.12	0.75	0.48	0.23
Shenyang	0.07	0.05	0.03	0.20	0.13	0.06
Shenzhen	0.59	0.41	0.24	1.09	0.70	0.33
Shijiazhuang	0.25	0.18	0.10	2.56	1.63	0.78
Singapore	0.04	0.03	0.02	0.02	0.01	0.01
Skopje	0.04	0.03	0.02	0.06	0.04	0.02
Stockholm	0.08	0.06	0.03	0.04	0.02	0.01
Surat	0.03	0.02	0.01	0.10	0.06	0.03
Suzhou (Jiangsu province)	0.27	0.19	0.11	1.51	0.96	0.46
Sydney	0.04	0.03	0.02	0.01	0.01	0.00
Taiyuan (Shanxi province)	0.10	0.07	0.04	0.38	0.24	0.12
Tallinn	0.04	0.03	0.02	0.02	0.01	0.01
Tashkent	0.01	0.01	0.01	0.02	0.01	0.01
T'Bilisi	0.26	0.18	0.11	0.35	0.22	0.11
Tegucigalpa	0.60	0.42	0.25	0.23	0.15	0.07
Tehran	0.20	0.14	0.08	0.60	0.38	0.18
Tel Aviv	0.14	0.10	0.06	0.33	0.21	0.10
Tianjin	0.25	0.18	0.10	1.36	0.87	0.42
Tirana	0.32	0.23	0.13	0.45	0.28	0.14
Tokyo	0.30	0.21	0.12	0.52	0.33	0.16
Toronto	0.05	0.03	0.02	0.03	0.02	0.01
Tripoli	0.06	0.04	0.02	0.15	0.10	0.05
Tunis	0.26	0.18	0.11	0.27	0.17	0.08
Ulaanbaatar	0.01	0.01	0.01	0.00	0.00	0.00
Ürümqi (Wulumqi province)	0.10	0.07	0.04	0.16	0.10	0.05
Vienna	0.08	0.06	0.03	0.09	0.06	0.03
Vilnius	0.04	0.03	0.02	0.03	0.02	0.01
Warsaw	0.09	0.07	0.04	0.11	0.07	0.03
Washington, DC	0.03	0.02	0.01	0.03	0.02	0.01
Wellington	0.05	0.04	0.02	0.01	0.01	0.00
Wenzhou	0.25	0.18	0.10	0.63	0.40	0.19
Windhoek	0.06	0.05	0.03	0.02	0.02	0.01
Wuhan	0.37	0.26	0.15	2.06	1.31	0.63
Wuxi (Jiangsu province)	0.35	0.25	0.15	1.69	1.08	0.52
Xiamen	0.18	0.13	0.08	0.44	0.28	0.13
Xi'an (Shaanxi province)	0.16	0.12	0.07	1.27	0.81	0.39
Xining	0.10	0.07	0.04	0.12	0.08	0.04
Yerevan	0.22	0.16	0.09	0.53	0.34	0.16
Yinchuan	0.14	0.10	0.06	0.26	0.17	0.08
Zagreb	0.04	0.03	0.02	0.05	0.03	0.02
Zhengzhou	0.29	0.20	0.12	2.58	1.65	0.79
Zhongshan	0.17	0.12	0.07	0.60	0.39	0.18

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Appendix II

Photo © Karine Aigner

Appendix 2: Methods

Overview

In this section, we describe the methods used in this study. First, we describe how we selected our study cities. Next, we describe how we conducted our review of the literature on trees and their mitigation of PM and temperature. Following that, we describe our calibration analysis, using high-resolution data to examine 34 cities in the United States and China. Note that our literature review and calibration analysis will also be described in a journal article (currently under review). Finally, we turn to our global analysis, describing the major analysis steps.

Cities studied

City selection

First, we began with a list of cities greater than 3 million people, as taken from the UNPD.[23] We then added national capitals of greater than 250,000 population (e.g., places like Stockholm). Finally, we added cities that were known priorities for The Nature Conservancy in regions. In the United States, for instance, this ensured that some smaller cities like Louisville, Kentucky, and Birmingham, Alabama were added to the analysis. In China, we chose to include all provincial capital cities. In total, there were 259 cities selected as candidate cities in our global analysis.

City boundaries

Boundaries for the cities come from a variety of sources. For most countries, we used the boundaries in the World Urban Areas layer distributed with ArcGIS 10. This, in turn, seems to be based primarily on the urban area maps created from MODIS imagery (and available free through Natural Earth). For some cities that were too small to be mapped in this imagery, we used the GRUMP urban area extents (e.g., Lhasa). For U.S. cities, we used the boundaries traditionally set by the U.S. Census. Specifically, we used the core-based statistical area definition of the U.S. Census, obtaining the boundaries for principal cities within the CBSA. This is necessary in the United States, because many metro regions have dozens or hundreds of different legal municipalities.

Data quality screen

After examining the available geospatial data sources, we ended up with a final list of 245 cities, listed in Appendix 1. Fourteen cities were dropped because the available geospatial data would not support accurate calculation of return on investment.

Out of this list of 245 cities, there were 30 cities where small portions of the city were data-limited. This occurred because the population density database (see below) was relatively coarse in portions of these cities. While these 30 poor-data-quality cities are in Appendix 1, because we believe their city-level metrics are accurate, we have not featured neighborhood-level data in the online website.

Additionally, there were nine cities that had apparently incomplete data for the global forest cover dataset we used because of clouds or banding issues with the Landsat imagery (Abidjan, Colombo, Kampala, Tehran, Fortaleza, Recife, Rio de Janeiro, Bogota, Detroit). While we think the neighborhood-level ROI data for these cities is generally accurate, care should be used when looking at forest-cover maps.

Similarly, the input data for particulate matter concentration seems to underestimate the concentration of PM in Lima, Peru. For consistency's sake, we did not do an ad hoc correction of the PM in Lima, but we note that our predictions of the effectiveness of trees in the city are likely conservative, underestimating the true effectiveness.

Literature review

The goal of this phase of the analysis was to survey the available literature on how trees reduce particulate matter concentrations or temperature, and then select a range of impact scenarios (High, Medium, and Low) that bracketed the uncertainty in the scientific literature. Our focus was on street trees, although we considered studies that also looked at larger patches if they contain information relevant to our report.

Particulate matter

In this section, we discuss removal of PM by trees, discussing both PM_{10} and $PM_{2.5}$, depending on the scientific paper.

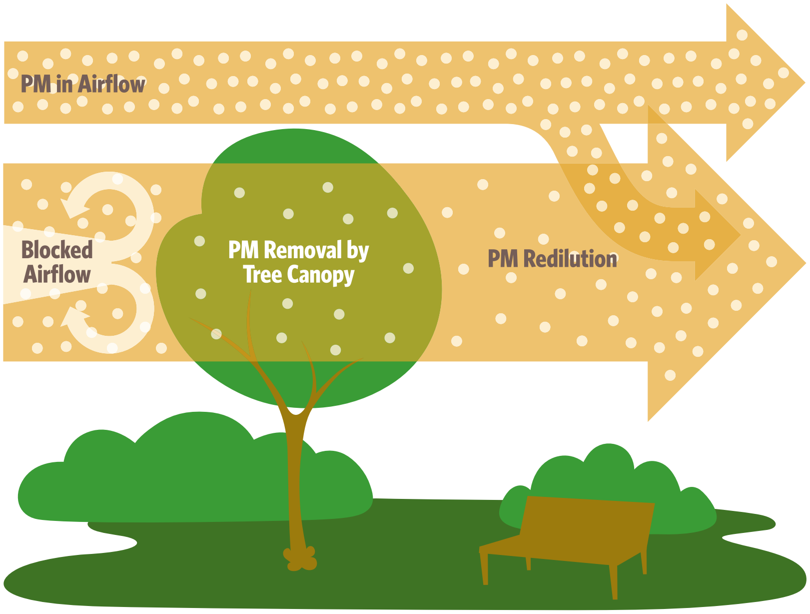

Figure 34. Diagram of PM removal by trees. Illustration: ©Mackinzie Jones.

Conceptually, there are three processes studied in the literature related to PM concentration and trees (Figure 34). First, there is the incoming airflow, which carries a certain concentration of PM (μg/m^3). Of course, this varies over time and space, depending on wind patterns and sources of PM emissions. In this global analysis, we look at average concentrations over an annual time step, and make the simplifying assumption that over that long time period, variations in wind direction average out. Second, the incoming airflow passes through the canopy, and a fraction of the PM is removed. This can be measured either as the percent reduction in PM during passage through the canopy, or as the removal in tons, or as a deposition velocity (the absolute rate of deposition per unit time). Note that some fraction of the incoming airflow is deflected instead of passing through the canopy, which can result in locally higher concentrations of PM upwind of a tree. Third, the cleaner air exits the canopy and continues moving downwind. Over some distance, this cleaner air mixes with other air that didn't pass through the canopy (redilution), and the concentration of PM approaches the average concentration for the region.

PM removal by tree canopy

Deposition velocity: One common way canopy removal of PM is measured is as a deposition velocity. This research approach is often used because deposition velocity is a key parameter in the process-level models of dry deposition. Most commonly, deposition velocity has been measured in closed forest stands or in rural settings. A relatively small number of studies[40, 41, 50] have directly measured deposition velocity in an urban setting (Table 22).

	Freer-Smith et al. 2005		**Mitchell et al. 2010[1]**		**Mitchell et al. 2010[2]**	**Langner et al. 2011**	
Location	Urban fringe (Sussex field site) Brighton, UK	Urban roadside park, high traffic (Withdean Park) Brighton, UK	Urban roadside, moderate-high traffic, Lancaster, UK	Background field site (Hazelrigg weather station), Lancaster, UK	36 sites around elevated stack point source, Oxfordshire, UK	High-traffic street canyon (site K-2a), Karlsruhe, Germany	Urban highway (site B-4b), Berlin, Germany
Vegetation type	Small tree stands		Saplings, single trees		Trees	Single row of mature trees	Small trees and shrubs
Classification for scaling	Urban, non-roadside	Urban roadside	Urban roadside	Urban, non-roadside	Urban, non-roadside	Urban roadside	Urban roadside
	A	B	C	D	E	F	G
Corsican Pine (*Pinus nigra*)	2.8	4.7					
Leyland Cypress (*Cupressocyparis leylandii*)	3.4	6.2					
Field Maple (*Acer campestre*)	3.6	1.8			1.9		
Poplar (*Populus deltoides trichocarpa*)	0.6	0.4					
Whitebeam (*Sorbus aria*)	5.4	3.3					
Birch (*Betula pendula*)			5	2	4.6		
Lime (*Tilia platyphyllos*)			2	2	2.4		
Sweet chestnut					0.5		
Willow					0.6		
Elder					0.8		
Elm					0.9		
Sycamore					1.3		
Horse chestnut					1.4		
Ash					1.5		
Beech					3.0		
Small-leaved lime (*Tilia cordata*)						1.7	
Norway Maple (*Acer platanoides*) and Sycamore Maple (*Acer pseudoplatanus*)							1.8

Notes:[1] Calculated from field measurements of magnetic PM$_{10}$. [2] Calculated by scaling v_d of magnetic PM$_{10}$ of lime and sycamore calculated from field measurements using ratios of magnetic PM$_{10}$ of these two and other analyzed species. v_ds s measured over time periods of 48 hours (averaged over three-week period) to one month (Mitchell et al. 2010); two weeks (Langner et al. 2011); and seven days (Freer-Smith et al. 2005), thus accounting for resuspension.

Table 22. PM$_{10}$ deposition velocities to urban vegetation, cm s^{-1}

Measured deposition velocity clearly varies greatly, by species as well as by type of site. This study focuses on roadside vegetation (columns B, C, F, and G in Table 22), which had a mean deposition velocity of 3.0 cm s^{-1}. There is considerable uncertainty in this estimate, though, and a one-standard-deviation range around our estimate would be from 1.1-4.9 cm s^{-1}. It is interesting to note that commonly used models of PM deposition use PM deposition velocities reported from older, non-urban study sites that generally have lower deposition velocities[43] or from laboratory experiments that may not accurately represent conditions at modeled sites. For instance, many implementations of the Urban Forest Effects model (also called UFORE or I-Tree)[51] are based on the average PM deposition values of Lovett 1994,[52] which was 1.28 cm s^{-1}. This suggests that UFORE and I-Tree estimates may be underestimating removal by roadside vegetation by a factor of 2.3 (i.e., the mean observed deposition from urban sites, 3.0, divided by the Lovett factor, 1.28).

There are other reasons to think that some modeled estimates of PM removal in the scientific literature may be underestimates. For example, air pollutant removal models such as the UFORE/I-Tree model[53] generally use ambient pollutant concentrations reported by U.S. EPA air-quality monitors as a key input. Because those monitors are often located away from major emission sources,[4] and because concentrations of PM and many other air pollutants decay to urban background levels over fairly short distances,[55] reported concentrations at monitoring sites may not adequately capture PM variability in an urban area[56] and may underestimate PM levels in areas located closer to emission sources,[57] as well as city-wide average concentrations.[58] With removal of many pollutants by trees being a linear function of ambient concentrations, *ceteris paribus*, such a systematic bias in concentration estimates may result in a substantial underestimate of modeled removal by vegetation in areas near emission sources[44] and city-wide average removal.[54]

Given this active discussion in the literature about the appropriate deposition velocity values for use in process-level models of dry deposition, and because the scope of our analysis prevented running such models for all 245 cities in our analysis, we decided to base our PM reduction estimates on empirical measurements of PM reductions in urban settings. Accordingly, we didn't use estimates of deposition velocity directly in our calculation, instead developing the approach described below. Note, however, that Kroeger et al. (in review) compared our methodology to the total removal that would be found using a deposition velocity approach, and found the two methods to give similar ranges of total removal (see box below).

Exponential decay inside canopies: Another approach used in the literature to quantify PM removal by trees is to examine how PM concentration changes in air moving through a canopy. The observed near-source PM mass concentration decrease in forest canopies can be fitted into an exponential function of patch depth,

$$C_X = C_0 e^{-kx}$$

where C_x and C_0 are the particle mass concentrations (µg/m^3) at horizontal distance x (in meters) from the edge of the canopy, and k is the depletion coefficient that incorporates vertical diffusion and deposition.[110] Three studies construct exponential PM_{10} removal functions.[48, 111, 112] Using data from another study done by Cavanagh and colleagues,[49] we could fit an exponential decay function to the reported PM concentrations from the outside monitoring, inside-near edge, and interior patch sites, with the sites chosen for their position along the trajectory of the prevailing wind. For trees, the range of decay coefficients in these studies is from k=0.019 (Cavanagh et al.,[49] mixed urban forest stand) to k=0.035 (Cowherd et al.,[48] tall dense oak and cedar trees).

Direct measurements of street tree effectiveness: A number of studies[43-49] measure the fraction of PM removed by street trees (Table 23), rather than using a decay coefficients approach. In this study, we estimate PM_{10} removal by street trees using the findings from the five experimental studies that analyze street tree PM_{10} capture efficiency (i.e., percent difference in PM_{10} in air upwind and downwind, respectively, of the trees).

Study	Vegetation	PM_{10} reduction (µg m^{-3})
Maher et al. (2013)	Row of small silver birch	50%
Mitchell and Maher (2009)	Single tree	15%
Bealey et al. (2007)	Two co-located trees	20%
Tiwary et al. (2008)	Hawthorn hedge	30%, 34%, 38%
Tiwary et al. (2006)	Hawthorn hedge	26%
Cowherd et al. (2006)	Tall dense oak and cedar trees	16%
Cavanagh et al. (2009)	Mixed urban forest stand	9%
This study- Medium scenario		*24%*
This study- Low scenario		*11%*
This study- High scenario		*37%*

Table 23. Downwind PM concentration reductions reported for street trees and hedges.

Because of the small number of observations in these (n=7, three of which are from the same study and plant), we generate two additional estimates using the high[48] and low[49] exponential PM_{10} concentration decay functions in the literature for tree patches for an assumed 5-meter canopy width. *We use the mean of the removal efficiencies reported in the five street tree studies as our central estimate, and the mean ± 1 SD to construct low (11 percent) and high (37 percent) estimates of street tree PM removal efficiency at the downwind canopy edge (Table 23).*

Comparison between PM_{10} and $PM_{2.5}$ removal: The majority of the literature on trees and PM focused on PM_{10}, but in the last few years, research has begun to increasingly focus on $PM_{2.5}$ as it has become apparent it has greater health impacts. This study focuses on $PM_{2.5}$, so we wanted some quantitative way to compare removal between PM_{10} and $PM_{2.5}$. Thankfully, there are several studies that empirically compare removal rates as a function of particle size.

- Maher and colleagues,[43] using continuous air samplers with particle size discrimination and saturation isothermal remanent magnetization (SIRM) analysis to assess PM removal achieved by a single row of young silver birch *(Betula utilis Doorenbos)* installed curbside in front of a row of houses along a high-traffic street, find that the trees reduced concentrations of both PM_{10} and $PM_{2.5}$ by >50 percent, indicating similar removal efficiency and thus $PM_{2.5}$ and PM_{10} deposition velocities. Cowherd and colleagues[48] also find that trees have comparable capture efficiencies for PM_{10} and $PM_{2.5}$, with 20-meter-wide belts of tall oak and cedar halving PM_{10} and $PM_{2.5}$ concentrations in air passing through them.
- Freer-Smith and colleagues[41] measured v_d PM_2 and PM_{10} for five tree species *(Pinus sylvestris, X Cupressoparis leylandii, Acer campestre, Populus deltoids, X trichocarpa* 'Beaupré' *and Sorbus aria)*, finding generally higher, but in some cases similar or lower v_d for PM_2 compared to PM_{10}, depending on species, and much higher (by one order of magnitude) v_d for PM_1 compared to PM_{10} (see Table 3 in[36]).
- Liu and colleagues[113] examined the daytime (0800 to 1800 hours) average daily PM removal of various land covers in the early spring (February to April 2013 and 2014) in North Olympic Forest Park in Beijing, China. They found that average removal efficiency (pollutant removal/ambient concentration) of a *Populus tomentosa*-dominated forest site was higher for $PM_{2.5}$ (~70 percent) than for PM_{10} (~60 percent).
- Chen and colleagues[114] examined the removal efficiency in August thru October of the same Beijing Populous shelterbelt studied by[113] Liu and colleagues and the removal efficiency of a *fraxinus chinensis* belt in Beijing. They found that the two shelterbelts had higher removal efficiencies for $PM_{2.5}$ than PM_{10}. Note that their use of the term "removal efficiency" is somewhat unusual, as the authors do not measure actual removal of PM from the air through dry deposition, but rather the ratio of PM concentrations inside and outside of two shelterbelts (one dominated by *populous tomentosa*, the other by *fraxinus chinensis*), interpreting higher concentrations inside the belts as "removal efficiency" because the belts effectively trap PM.

The above papers (with the exception of[41] with the exception of Freer-Smith and colleagues) show that trees are at least as effective in removing $PM_{2.5}$ as they are in removing PM_{10}. *In this report, we make the conservative assumption that PM_{10} and $PM_{2.5}$ removal rates, in percent terms, are the same.* Of course, in mass terms, since there is a greater mass of PM_{10} in the atmosphere than $PM_{2.5}$, a greater mass of PM_{10} will be removed.

Redilution

The horizontal distance downwind of a patch within which the lower-PM air exiting a patch is sufficiently mixed with ambient air to substantially dilute the concentration reduction effect produced by a tree patch depends on wind speed (advection) and turbulent mixing (diffusion) within the urban canopy layer (approximately up to roof height), which are strongly influenced by urban surface morphology and vertical mixing.[59, 60, 115] Empirical studies show that PM in urban areas is well mixed over distances of 2.5 meters to 300 meters.[55, 58, 116-119]

The PM decay functions reported by three edge-of-road studies—including a meta-analysis of PM concentration distance decay studies,[55]—that represent a wide range of meteorological, urban morphological, and methodological contexts show exponential decay with inflection points at 15 meters, 50 meters, and 66 meters, respectively, from the edge of the road. Based on these findings, we assume that the effect of PM removal by trees is most pronounced within a distance of 15 meters to 30 meters downwind—e.g., Maher and colleagues[43] report street trees halved indoor PM concentrations in houses approximately 10 meters away—but generally still is notable at 65 meters downwind, indicated by the negative slope of the functions at that distance.

To estimate the PM reduction a particular addition of street trees in a given street segment achieves within a 30-meter buffer from the street edge, we use our function of average PM concentration as a function of distance from the tree canopy (Figure 35). This function describes how much (expressed in percent) of the PM concentration reduction achieved by a given tree canopy still remains at given distances downwind from the canopy, up to the point at which the mixing with other ambient air results in concentrations similar to the ambient PM background levels.

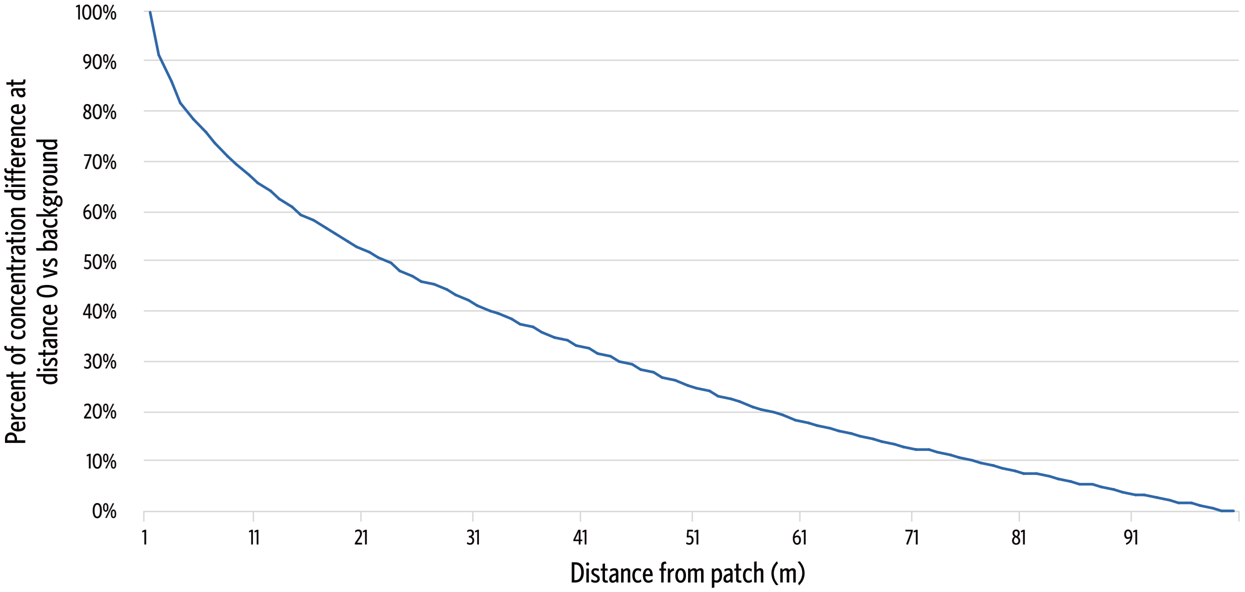

Figure 35. Average PM concentration as a function of distance from street trees.

Average percent reduction achieved within 30 meters of street trees

Assuming trees are on average planted 1.5 meters from the road edge and have an average canopy diameter of 5 meters, we calculate the mean percent PM_{10} reduction experienced across the remaining 26 meters of buffer downwind of the canopy as the average of the PM_{10} reductions experienced at every 1 meter step along a perpendicular transect through the buffer, and multiply this average reduction by the percent PM concentration reduction achieved by street tree canopy. *This yields an estimated mean PM_{10} concentration reduction in the buffer (compared to ambient urban concentrations upwind of the trees) of 7 percent, 16 percent and 24 percent in the Low, Medium, and High removal scenarios, respectively.*

Next, because our estimated PM removal efficiencies are based on studies of conifers or leaf-on broadleaf species (except Kuhns et al. 2010,[111] who study leafless aspen trees), we derive average annual PM concentration reductions by multiplying our calculated PM concentration reductions by the annual average share of time a given city's trees are in-leaf, calculated from remotely sensed phenology information for each city (see geospatial data). We then multiply the resulting reductions by the calculated average annual 2014 $PM_{2.5}$ concentrations in the respective segment and buffers to obtain the estimated average annual $PM_{2.5}$ concentration reduction (in µg $PM_{2.5}$ m^{-3}) a particular street tree planting achieves in the sector of the segment's buffer adjoining the planting (see note above about converting from PM_{10} to $PM_{2.5}$ percent removal). Given that street tree cover additions will be linear in shape, the percentage of a planting site's total segment buffer area and population that are located in the planting's adjoining buffer sector are assumed to be proportional to the percent increase in segment tree cover. We multiply for each street tree planting the estimated absolute $PM_{2.5}$ concentration reduction in its adjoining buffer sector by the estimated population within that portion to estimate the increase in street tree cover would produce for people living in that segment (Δµg $PM_{2.5}$ m^{-3} people).

Box 6: Calculating total removal in an airshed

Nowak and colleagues[53] popularized a way of calculating total potential removal of PM by trees in an entire airshed above a city, based off the UFORE/i-Tree model. Results were presented in total tons of PM removal, as well as the percent of the total pollutant load that was estimated to be removed by trees currently. Generally, estimated removal was modest, between 0.1 percent to 3.5 percent depending on the city and the scenario. This modest percet removal of the entire pollutant load in an airshed has been, in part, why some reviewers of the literature have expressed some skepticism that PM removal by trees can be substantial.

How is it possible that Nowak and colleagues can calculate such a modest benefit for an entire airshed, while empirical measurements of capture efficiency just downwind of tree are much larger, ranging from 9 percent to 50 percent (Table 22) The difference primarily has to do with the spatial scale. Nowak and colleagues were comparing tree removal to the entire pollutant load in an airshed, defined as from the ground up to the boundary layer, often hundreds of meters in the air. This is a huge quantity of air, which can hold huge masses of PM. In contrast, empirical measurements happen near the ground, where people breathe, and are in proximity to trees. The local packet of air moving through the trees can be significantly cleaned, although it eventually redilutes into the overall airshed.

Kroeger and colleagues (in review) present a comparison of Nowak and colleagues' estimates of total removal, compared with our estimates of total removal derived from direct measurements of street tree effectiveness. Once the spatial difference (whole airshed versus local benefits) is accounted for, the total annual removal, expressed in grams of PM per per square meter of canopy (to account for differences in forest cover) is quite similar. Nowak's estimate, corrected for today's PM concentrations (lower than the data he used for his study) and recent measurements of deposition velocity (higher than for the Lovett citation he bases his work on), would be 4.1 to 11.0 g/m². For our estimates of total removal, the equivalent range would be 6.5 to 13.2 g/m².

It is for this reason that throughout the report we have stressed the local removal of PM by trees. *Trees can remove quantities of PM that can be medically significant to those living in proximity of the trees, even if the percent removal over the entire airshed is rather modest.*

Temperature

There are two conceptual stages of how trees cool air temperatures (Figure 36). First, depending on the width of the tree canopy (or, in the case of a forest patch, the width of the forest patch), there is a cooling intensity, which is defined as the degree Celsius reduction relative to the average air temperature outside the patch. Generally, the larger the canopy, the greater the cooling intensity. Second, this cooler air disperses away from the patch, and slowly mixes with other warmer ambient air. Generally, the farther from the canopy, the closer the temperature gets to the average temperature in the surrounding area.

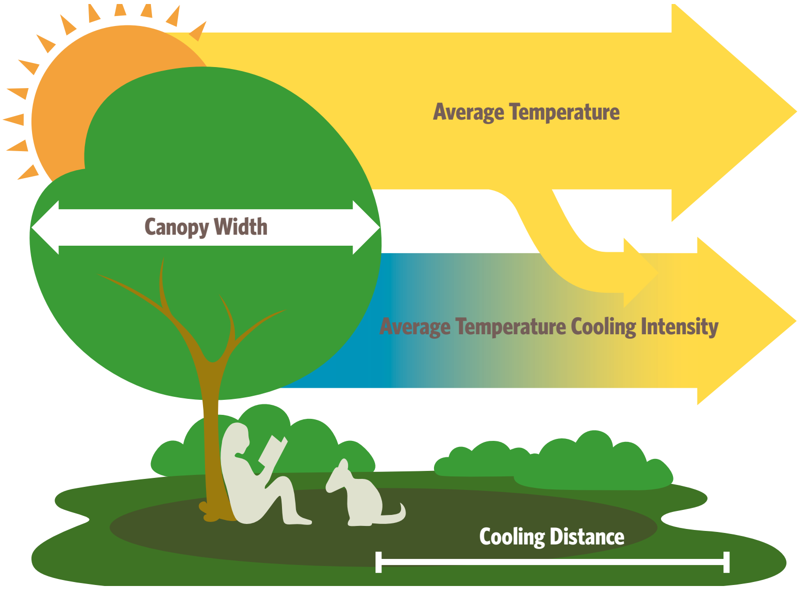

Figure 36. Diagram of temperature mitigation by trees. Illustration: © Mackinzie Jones.

Cooling intensity

Table 24 lists some results for studies[66, 67, 69-71, 73, 75-77, 79-83, 120-129] that examined relatively large urban parks. The cooling intensity varies from close to zero to 6.7° C (12.1° F), depending on the site, the time of day, and the distance at which the measurement was taken from the park. For the purposes of our analysis, we were interested in measurements of cooling intensity within or very close to the park, before the effect began to decay with distance. These measurements close to the parks are generally higher. See Kroeger et al. (in review) for a more detailed analysis of this set of studies on parks. Since the focus of this report is on street trees, we do not use the information in Table 24 in our global modeling.

Table 24. Empirical and modeling studies of the summer ambient air temperature cooling effect of forested or mixed-cover parks and urban forests.

Study	Park size	Land Cover	Location	Temperature reduction	Measurement specification
Taha et al. (1991)	4.9 ha	small trees (H=5 m), 25% canopy cover; narrow belt of tall (20m) dense evergeen trees (90% cover)	Davis, CA	4.5° C	Reduction in peak temp (16:00) compared to upwind, adjacent, open, dry field; clear sky; October (location D minus A, fig. 2)
	4.91	(including avg 10,-wide evergreen tree along southern edge of orchard)		5.5° C	Reduction in peak temp (17:00) compared to upwind, adjacent, open, dry field; October
				1.5° C	Reduction in peak temp (16:00-18:00) compared to upwind, adjacent, open, dry field; October
Ca et al. (1998)	60 ha	Mix of woods, grass and some sealed surface	Tama (Tokyo Met Area), Japan	2.2° C	Reduction in sunny August afternoon air temp above grass field inside park, compared to air temp above sealed areas surrounding
				1.5° C	Reduction in sunny August noon air temp in commercial district 1 km downwind
Sugawara et al. (2016)	20 ha (0.2 sq km)	90% deciduous forest, 14 m mean canopy height	Tokyo, Japan	3° C	Difference between summer (Aug-Sep) peak daytime (2 p.m.) temp in park and surroundings (school gardens within 1.5 km from park)
Dimoudi and Nikolopoulou (2003)	0.01 ha, Street H/W ratio=1.5	Typical Mediterranean vegetation (e.g., olive and citrus trees)	Athens, Greece	2° C	Temp difference at downwind edge of park facing building, if park replaces building of same dimensions
				4° C	Temp difference at downwind edge of park in street parallel to park, if park replaces building of same dimensions
	0.03 ha, Street H-W ratio=1.5			3° C	Temp difference at downwind edge of park facing building, if park replaces building of same dimensions
				6° C	Temp difference at downwind edge of park in street parallel to park, if park replaces building of same dimensions
Jaganmohan et al. 2016	Urban forests (n=25), median size 2.2 ha	96.5% mean tree/ shrub cover	Leipzig, Germany	0.3° C	Mean of the maximum daytime (9 a.m. to 5 p.m.) temp difference in summer (June-Aug) on clear sunny days in residential areas, at 1 PWD from forests, compared to forest boundary
				0.8° C	Mean of the maximum daytime (9 a.m. to 5 p.m.) temp differences in summer (Jun-Aug) on clear sunny days, between forest boundary and anywhere in residential areas within 1 PWD from forests
	Urban parks (n=37)	74% mean tree/ shrub cover		0.1° C	Mean of the maximum daytime (9 a.m. to 5 p.m.) temp difference in summer (Jun-Aug) on clear sunny days in residential areas, at 1 PWD from parks compared to park boundary
				0.5° C	Mean of the maximum daytime (9 a.m. to 5 p.m.) temp differences in summer (Jun-Aug) on clear sunny days, between park boundary and anywhere in residential areas within 1 PWD from parks

Study	Park size	Land Cover	Location	Temperature reduction	Measurement specification
Chen and Wong (2006)	36 ha	Mix of densely forested, sparsely forested and open sites	Singapore	3° C	Mean difference between average temp of densely forested park sites (# 3 and 4) and nearby residential sites at 15:00 on clear summer (Jan-Feb) day
				2° C	Mean difference between average temp of all park monitoring sites and nearby residential sites at 15:00 on clear summer (Jan-Feb) day
	12 ha	Mix of densely forested, sparsely forested and open sites	Singapore	4° C	Mean difference between average temp in densely forested park site (#1) and nearby residential sites at 15:00 on clear summer June day
				2° C	Mean difference between average temp of all park monitoring sites and nearby residential sites at 15:00 on clear summer June day
Ketterer and Matzarakis (2014)	n/a	Treed area: 19% tree cover; 34% impervious; 28% built; asphalt area: 3% tree cover, 47% impervious; 17% built	Stuttgart, Germany	1.2° C	Mean temp difference between asphalt and treed area in early-mid afternoon (14:00 to 17:00) on clear summer (late June) day
Legese Feyisa et al. (2014)	21 urban forest parks (0.85-22.3 ha)	>60% tree canopy cover	Addis Ababa, Ethiopia	3.9° C	Average (11:00 to 16:00 hours) temp difference between park and surroundings (from park boundary to 420-meter distance contour) in summer (October, end of rainy season)
				6.7° C	Maximum (11:00 to 16:00 hours) temp difference between park and surroundings (from park boundary to 420-meter distance contour) in summer (October, end of rainy season)
				0.02° C	Mean increase in park cooling intensity per 1% increase in tree canopy cover, 11:00 to 16:00 hours, compared to surroundings (from park boundary to 420-meter distance contour) in summer (October, end of rainy season)
Skelhorn et al. (2014)			Manchester, UK	0.15° C	Mean area-wide temp reduction at neighborhood level, 13:00 to 16:00 hours, summer (July), from adding 5% mature trees
Ng et al. 2012	0.01 ha		Hong Kong, China	1° C	Mean temperature reduction in pocket park compared to surrounding built-up area at 1 PWD, 15:00 to 16:00 hrs, May (summer)
Cohen et al. (2012) (same site as Potchter et al. 2006)	3 urban parks, 0.4-3.6 ha, 65-85% mature tree cover		Tel Aviv, Israel	2° C	Mean temp difference between treed parks and non-treed urban areas summer (June-July) w/ generally clear skies and moderate wind
	2.8 ha, 85% mature tree cover		Tel Aviv, Israel	3.8° C	Maximum temp difference between treed park and non-treed urban areas summer (June-July) w/ generally clear skies and moderate wind
Spronken-Smith and Oke (1998)	1.4 ha Forested park (Botanical Garden)		Sacramento, CA	1.2° C	Maximum summer daytime (August) temperature difference compared to non-park area
	400 ha dense conifer rainforest (Stanley Park forest)		Vancouver, BC	4.0° C	Maximum summer daytime (August) temperature difference compared to non-park area (temps of which were measured mostly on roads)
Hamada and Ohta (2010)	147 ha	40% cemetery; 36% forest, 4% grass, 4% ponds, 5% fields, 10% badlands	Nagoya, Japan	2.5° C	Maximum temperature difference at 3 p.m. between forested site in park vs urban area, August 2006 (see p. 21)

Study	Park size	Land Cover	Location	Temperature reduction	Measurement specification
Chang et al. (2007)	<3 ha	≥80% tree and shrub cover (Fig 5a)	Taipei, Taiwan	2° C	Reduction in air temp between open (unshaded) area in park and surroundings >1 width of the park away from park, on sunny, non-windy (<2.1 m/s wind speed) summer (Aug-Sep) days, 11:00 to 15:00 hrs
	>3 ha	≤25% paved area (Fig 5c)		1.8° C	Reduction in air temp between open (unshaded) area in park and surroundings >1 width of the park away from park, on sunny, non-windy (<2.1 m/s wind speed) summer (Aug-Sep) days, 11:00 to 15:00 hrs
Chang and Li (2014)	<0.5 ha	n/d	Taipei, Taiwan	n/d	Reduction in air temp outside of park vs refernce point just >1 park width away from park, on sunny, non-windy (<2.1 m/s wind speed) summer (Aug-Sep) days, 11:00 to 15:00 hrs
	<0.5 ha (mean: 0.23 ha)	n/d		0.75	Reduction in air temp at park boundary vs refernce point just >1 park width away from park, on sunny, non-windy (<2.1 m/s wind speed) summer (Aug-Sep) days, at noon (11:00 to 15:00)(right upper panel in Fig 2)
	>0.5 ha	Average cool-island park (composed of trees, shrubs, open, and paved areas)		0.3° C	Reduction in air temp outside of park vs reference point just >1 park width away from park, on sunny, non-windy (<2.1 m/s wind speed) summer (Aug-Sep) days, 11:00 to 15:00 hrs
	n/d	>75% tree and shrub cover		0.8° C	Reduction in air temp outside of park vs refernce point just >1 park width away from park, on sunny, non-windy (<2.1 m/s wind speed) summer (Aug-Sep) days, 11:00 to 15:00 hrs
Barradas 1991	9.9 ha	mix of vegetation and pavement	Mexico City, Mexico	3.1° C	Difference between mean peak afternoon temperatures in parks and in surroundings, May-Nov (Fig 3 A and B)
	1.9 ha		Mexico City, Mexico	0.9° C	Difference between mean peak afternoon temperatures in parks and in surroundings, May-Nov (Fig 3 A and B)
Jonsson (2004)	n/a	Lush vegetation including trees	Gaborone, Botswana	1° C	difference in avg daily max (14:00) temperatures on clear, calm spring days, between lushly vegetated site and site with only a few sparse trees (both non-irrigated)
Jauregui (1991)	525 ha	Mix of dense forest, grass and paved and built-up areas.	Mexico City, Mexico	2 to 3° C	Difference in mean maximum temperatures (14:00) between park boundary and nearby built-up areas
Lee et al. (2009)	24.2 ha	Tombs, mature forest (*Pinus densiflora and Quercus* spp) and grassy areas	Seoul, South Korea	3° C	avg 15:30 July-Aug air temp difference between park and nearby reference site
Shashua-Bar and Hoffmann (2000)	11 small green areas, 0.05-1.1 ha (avg. 0.4 ha)	Dense tree cover (avg partially shaded area=61%)	Tel Aviv, Israel	2.8° C	Mean difference in summer maximum daily (15:00) air temperatures between 11 green areas and nearby treeless reference points at 50 to 100 meters distance, on clear, calm days
				1.77° C	Avg cooling effect at 20 meters
				1° C	Avg cooling effect at 40 meters
				0.67° C	Avg cooling effect at 60 meters
				0.3° C	Avg cooling effect at 80 meters

Study	Park size	Land Cover	Location	Temperature reduction	Measurement specification
Saito et al. (1990)	0.24 ha	Urban park covered with broadleaf trees	Kumamoto City, Japan	1 to 2° C	Avg. temp reduction within approx. 20-meter distance from greenspace boundary
				3° C	Max daytime temperature difference
Streiling and Matzarakis (2003)	0.03 ha; Small cluster of trees in 0.17 ha urban park enclosed by three high-traffic roads and including grassy and bare/paved areas		Freiburg, Germany	0.8° C	Mean air temp difference (1 to 3 p.m., 2 mid-late September days) under small cluster of tree canopies compared to nearby open sealed surfaces (measurement points MP2, MP4, and MP5)
	0.01 ha; Individual tree in 0.17 ha urban park enclosed by three high-traffic roads and including grassy and bare/paved areas		Freiburg, Germany	0.7° C	Mean air temp difference (1 to 3 p.m., 2 mid-late September days) under a single tree canopy compared to nearby open sealed surfaces (measurement points MP2, MP4, and MP5)
Shashua-Bar et al. (2011)	Individual tree (7-meter-wide wide canopy) (from Fig. 1)	Tree vs concrete	University campus, Negev Desert, Israel	1.7° C	2 p.m. temp reduction of trees vs. light grey concrete surface w/out trees, mean, July-Aug (summer)
	Individual tree (7-meter-wide canopy) (from Fig. 1)	Trees vs grass cover	University campus, Negev Desert, Israel	1.3° C	2 p.m. temp preduction of trees vs. grass cover, mean, summer (July-Aug)
Taleghani et al. (2014)	Heavily treed park		Portland, OR	5.8° C	Maximum temperature difference between heavily treed park and nearby parking lot
			Portland, OR	1.6° C	Temperature difference between treed and bare courtyard

Table 24. Empirical and modeling studies of the summer ambient air temperature cooling effect of forested or mixed-cover parks and urban forests.

Rather, we use estimates of cooling intensity of street trees,[62, 64, 65, 70, 75-79] which include observations from a total of 31 high-canopy streets or individual street trees and span a wide range of climates (Figure 37). Cooling intensity varies from 0.4° C (0.7° F) to 3.0° C (5.4° F), depending on the site and the time of day.

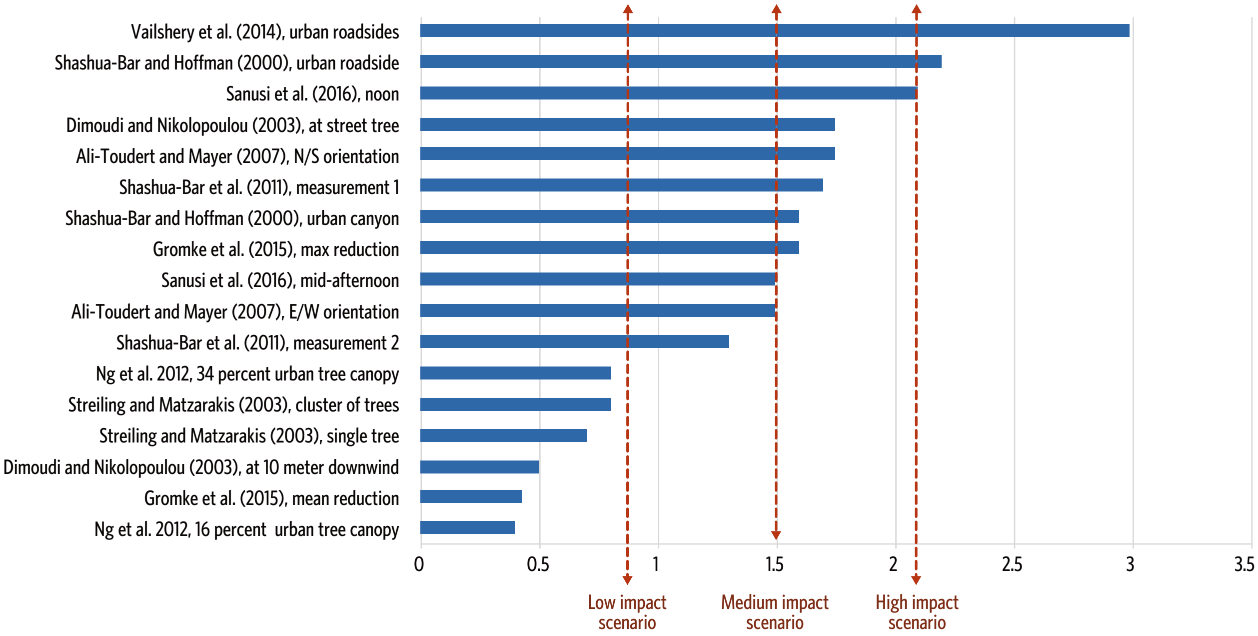

Figure 37. Empirical measures of temperature reduction near urban trees. Dashed lines show the three scenarios of Low, Medium, and High impact used in this global analysis.

Cooling distance

As you move away from a canopy, temperatures slowly increase toward the ambient temperature in the surrounding area. The only study we found that provided empirical observations of street tree temperature change as a function of distance from tree was Shashua-Bar and Hoffman.[79] We estimate a best-fit (linear; $R^2=0.98$) cooling distance function from the means of the empirical cooling values reported at zero-, 20-, 40-, 60-, and 80-meter distance (*x*, in meters) from trees for four treed streets vs two reference sites each (n=8) (Figure 38).

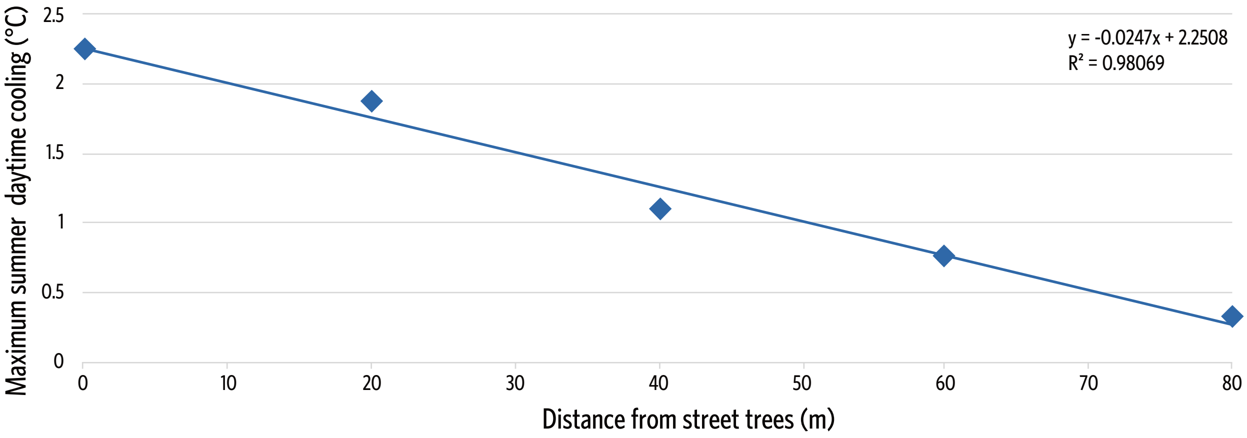

Figure 38. Average street tree cooling effect as a function of distance from street trees.

Average temperature reduction

We use our cooling function and the mean of the reported cooling intensity of Shashua-Bar and Hoffman's[79] four treed streets at $x = 0$ to calculate the percent of the remaining cooling intensity at distance x from street trees. We multiply the average of the percent residual cooling intensity along a transect through the street tree buffer estimates to calculate the absolute (Low, Medium, High) reduction in mean temperature in the street tree buffer. To do so, we assume that trees are planted 1.5 meters from the street and (at maturity) have a canopy radius of 5 meters. This works out to an average reduction in the street tree buffer of 0.9° C (Low scenario), 1.5° C (Medium scenario), and 2.1° C (High scenario) (Figure 37).

As with PM, because we lack information on the distribution of people within a street segment buffer, we assume the human population affected by cooling from additional street tree plantings is proportional to the percent street tree addition in a segment.

Calibration analysis

The primary purpose of the calibration analysis, from the perspective of this report, was to help us statistically relate the 30-meter Landsat forest cover data available globally with high-resolution 2-meter forest cover data. It would not have been feasible to develop high-resolution forest cover datasets for all 245 cities in our analysis. However, we know from past research that forest cover derived from Landsat imagery doesn't do a great job of detecting single trees, like those along streets. We thus wanted to calibrate or correct for any bias in using the Landsat data.

Note, however, that the calibration analysis also fed into the analysis in another companion scientific paper, Kroeger et al. (in review). This paper developed ROI metrics for every street segment and patch in the calibration cities. These detailed ROI metrics are not referenced in this report, except for the comparison of Map 8. It is reassuring, however, that the ROI metrics of Kroeger et al., developed from the most detailed possible geospatial data, are highly correlated with the ROI numbers we developed in this global report.

There were 27 U.S. calibration cities and seven Chinese calibration cities. Because one of the purposes of the calibration analysis was to compare the results of city-level and local-level methods for estimating PM and heat impact of urban street trees, we selected cities for inclusion in the study primarily based on availability of UFORE/i-Tree estimates of average city-wide PM_{10} removal rates by urban forests.[53]

Comparison of forest cover data sources at different scales

High-resolution Forest Cover

We developed our own high-resolution (2-meter) tree cover maps for the 34 total calibration cities. For U.S. cities, we based our tree cover maps on aerial photos from the United States National Agriculture Imagery Program (NAIP). For Chinese cities, we based our tree cover maps on imagery from the Gaofen-1 (GF-1) satellite, acquiring pan-sharpened and orthorectified imagery for our seven cities of interest.

For all 34 cities, we used Google Earth Engine to classify the imagery. First, we extracted the Normalized Difference Vegetation Index (NDVI) for each city's extent. The threshold of NDVI that was assumed to indicate forest cover was adjusted to each city accordingly as imagery varies across the United States, and then visually checked for accuracy. Results from aerial photo classification was then resampled to 2 meters, to increase accuracy by excluded very small areas of NDVI which were not trees. Second, we extracted texture analysis (based on entropy), adjusted to each city accordingly as imagery varies across the United States.[130, 131] Finally, in ESRI ARCMAP 11.2, NDVI and Texture results combined to exclude areas of NDVI data and smooth texture (correlates with gold-courses, sports fields, lawns) to produce a 2-meter tree cover layer.

Global Forest Cover

For our global analysis, we use 30-meter resolution continuous percent forest cover estimates for the years 2000 and 2010,[132] hereafter called the Vegetation Continuous Field data (VCF). To statistically account for street trees which often may not be detected by 30-meter imagery, we calibrate the VCF estimate to the 2-meter high resolution percent forest cover data using the empirical relationship between the two datasets in our study cities (Figure 39).

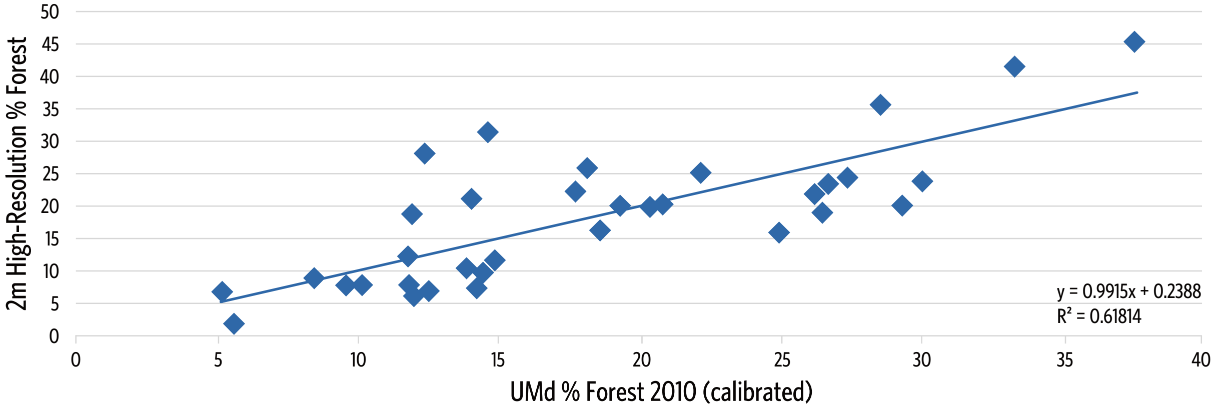

Figure 39. The statistical relationship between the VCF 30-meter forest cover estimates (calibrated as described in the text) with the 2-meter high-resolution forest cover maps created for this report.

Global Forest Cover Change

One challenge in comparing between VCF forest cover images from 2000 and 2010 is that in some locations there is a systematic shift in pixel values that seems to be due to calibration errors rather than any landscape-wide change in vegetation cover. To account for this, we classify all pixels in each city as showing *significant (>25 percent) decrease or increase, or no significant (≤25 percent) change* in percent forest cover between 2000 and 2010, with the 25 percent threshold being approximately two standard errors of the distribution of change. For each forest cover change category, we calculate mean percent forest cover change in 2000 and 2010. Assuming that forest cover differences in the *no significant change* category are primarily due to changes in the remotely sensed imagery, we generate centered percent forest cover estimates by subtracting 2010 percent forest cover from 2000 percent forest cover and adding this difference to the 2000 percent forest cover values in each pixel, thus normalizing the two distributions.

Global analysis

Geospatial data

There were nine types of spatial data that we obtained for all 245 of our cites:

- Particulate matter concentrations—We took $PM_{2.5}$ concentrations for 2012 for our cities from van Donkelaar et al.[133, 134] which developed improved global estimates of $PM_{2.5}$ concentrations from remotely sensed imagery.
- Land cover—We used 30-meter land cover imagery taken from the GlobeLand30 LULC product.[135]
- Forest cover—We used continuous estimates of percent forest taken from UMd dataset.[132]
- Biome types—We defined biome type using the typology in the WWF ecoregions.[136]
- Road network—Information on the road network was extracted from Open Street Map.[137]
- Schools—Information on schools was extracted from Open Street Map.[137]
- Hospitals—Information on hospitals was extracted from Open Street Map.[137]
- Population density—Population density information was taken from the Gridded Population of the World Database, version 4.[138]
- Phenology—We estimated growing season length using the Vegetation Index and Phenology (VIP) lab products, version 3.[139]

GIS Analysis

Our GIS analysis aimed to sample out relevant data for each of our study cities. The first step was to create a 1-kilometer grid that covered the area of a city. Each grid cell is assigned a unique identifying number. Within each grid cell, the length of streets (in meters), the population density (in people/km^2), the $PM_{2.5}$ concentration (in µg/m^3), the biome type, and the percent forest, calculated only for pixels along the road network.

Our GIS analysis was done using a Modelbuilder script in ArcGIS 10.3.1 for Desktop. This Modelbuilder script was then called from a Python loop that iterated through the datasets for all 245 cities.

Maximum possible street tree-planting targets

Within each biome category, we examined the distribution of percent forest, restricting our examination to 1-kilometer cells that had at least 10 cells of 30-meter forest imagery. In most biomes, there is a range of street tree cover, from 0 percent to close to 100 percent. We wanted to set a street tree-planting target that was realistic, and clearly on many streets a 100 percent street tree cover is not realistic, due to planting limitations. In the end, we set a target at the 95 percentile of current street tree cover in each biome. That is, we assume that since one in 20 streets in this biome already exceed this level of cover, it will be possible to achieve this level of tree cover on other streets in the biome. We acknowledge that this is a relatively crude way to estimate maximum possible street tree-planting targets, and we urge future analyses that focus on a particular city to use more precise definitions.

Two biomes had very low (< 10 percent) values of the 95 percentiles, and these were set at 10 percent for this study, to make a more ambitious tree-planting target (Table 25).

Biome name	Maximum possible street tree-planting target (%) used in this study
Tropical and Subtropical Moist Broadleaf Forests	27.2
Tropical and Subtropical Dry Broadleaf Forests	10.0
Tropical and Subtropical Coniferous Forests	28.8
Temperate Broadleaf and Mixed Forests	51.7
Temperate Coniferous Forests	53.1
Boreal Forests/Taiga	73.0
Tropical and Subtropical, Grasslands, Savannas, and Shrublands	30.3
Temperate Grasslands, Savannas, and Shrublands	25.9
Montane Grasslands and Shrublands	11.5
Mediterranean Forests, Woodlands, and Scrub	17.8
Deserts and Xeric Shrublands	10.0
Mangroves	18.5

Table 25. Street tree-planting targets by biome.

Tree-planting and maintenance costs

We based our analysis of tree-planting costs on a database we assembled of both planting and maintenance costs for cities. These were expressed as annualized costs, spreading the costs of planting over 40 years. We found estimates of tree-planting and maintenance costs for 27 U.S. cities and seven Chinese cities. These estimates were developed originally for the Kroeger et al. manuscript (in review), but are used in this global study.

To make our estimates of cost more globally comprehensive, we searched the literature and found eight more cities/countries where we found street tree-planting and maintenance estimates. Merging this information in with our U.S. and China data, we find that there is a positive correlation (R2=0.57) between per-capita GDP in a country (Purchasing Power Parity, PPP, corrected) and the annualized costs (also PPP corrected). That is, countries of a higher-level of economic development have, on average, higher per-capita planting and maintenance costs. This could be explained, for instance, by higher average labor costs in cities. In our global analysis, we used this correlation and average PPP-GDP per capita to estimate annualized street tree costs for all the cities in our sample.

Particulate matter and temperature analysis

Using code in Statistical Analysis Software (SAS), we analyzed the output of the GIS analysis to calculate the current and potential future reductions by street trees of $PM_{2.5}$ and temperature. In our SAS analysis, we look at a High, Medium, and Low impact scenarios, based upon the literature. See our literature review for evidence on how these scenarios were defined.

For each 1 square kilometer, we estimated the ROI (PM and temperature) of a small planting along a single street segment. We also estimated the potential future planting in the square, as well as the reductions in PM and temperature.

Health impacts analysis

PM reduction

There are a number of papers that estimate a functional relationship between ambient PM concentrations and mortality rate.[89, 90] The functional form used varies among papers. Early papers found an essentially linear relationship between ambient PM concentrations and mortality rates. This implies that at low concentrations, there is no safe limit of PM—any amount of PM has an impact on mortality rates. Later papers explored different functional forms, which were particularly important for accurate estimation of mortality at very high concentrations of PM. Burnett and colleagues offer a good review of the various functional forms in use.[90] For our calculations, we follow the recommendations of the World Health Organization,[91] because they have been widely used and are relatively simple to implement.

Temperature reduction

There are a few studies estimating the regression relationship between temperature and mortality.[14, 20] Most functional forms look at the mortality increase when ambient temperature increases above a certain threshold temperature. There is debate in the literature whether this functional response is best fit with a linear or an upward curving functional form (e.g., quadratic). There is also a lot of research into the ways urban residents adapt to the average summer temperatures in their region. That is, in cities that generally have hot summer weather, it takes extremely hot weather to cause an increase in mortality. In contrast, in cities which more often have moderate summer temperatures, an increase in mortality sets in at lower absolute temperature increases. That is, the threshold temperature at which mortality appears to increase seems to be related to the climatic average for a region.

For this report, we use the relatively simple methodology used by McMichael and colleagues,[14] which uses a linear relationship between mortality and temperature above a safe threshold. The safe threshold varies by climate zone (Table 20.5 in McMichael and colleagues[14]).

Electricity and carbon sequestration analysis

Another co-benefit of street trees is that they can help mitigate climate change, either through directly sequestering carbon itself or (more importantly) by reducing electricity use for cooling and hence greenhouse gas emissions. The effect of trees on electricity use for cooling operates in two main ways: Shade from trees reduces the direct solar heating of homes, reducing the need for air conditioning; and trees can reduce ambient air temperatures, which thus lessens the need for cooling of the air inside homes.[94] One set of studies have modeled and measured the benefits that trees can provide, primarily to residential single-family homes. For instance, McPherson and Rowntree[95] report a 2- to 9-percent reduction in annual heating and cooling costs from a single well-placed tree. Another set of studies have looked at the empirical relationship between ambient temperature and electricity use. A recent review by Santamouris and colleagues[96] found that each increase in temperature of 1°C (1.8°F) caused an increase in monthly residential electricity use from 4 to 8.5 percent.

A number of factors affect the magnitude of this reduction in residential electricity use and hence the avoided greenhouse gas emissions:

- **Orientation:** Trees on the sunnier side of a house (e.g., the south side of a house in the Northern Hemisphere) cause a greater reduction.
- **Distance to house:** Trees closer to the house have more of an impact.
- **Size and density of canopy:** Canopies that cast more shade cause a greater reduction.
- **Size and construction of building:** More of the published research showing benefits is for "one- or two-story houses, with individual or small clusters of trees appearing to have less of an effect on the electricity use of larger buildings.
- **Type of energy used:** Obviously, the greenhouse gas implications of a reduction in electricity depend greatly on the carbon intensity of electricity production. Electricity produced from coal, for instance, causes more life-cycle greenhouse gases than electricity from hydropower.

It is beyond the scope of this report to fully account for all these factors. Nevertheless, we wanted to construct a rough estimate of how the kind of street tree planting considered in this study would impact electricity use and greenhouse gas emissions. We base our estimate on the range of effects shown by Santamouris and colleagues.[96] Note that our analysis only considers street trees (not trees in parks, forest patches, private yards, etc.), and we only consider the potential energy savings to residential electricity consumption for cooling. Furthermore, our assumptions about plausible planting targets (see discussion above) mean that at most only a fraction of homes benefit from an electricity reduction. It is not plausible for all homes in a neighborhood to be helped by additional street tree planting.

For carbon sequestration, we base our analysis on the minimum and maximum values of net sequestration observed by Nowak and colleagues.[98] We acknowledge that applying these U.S. values to a global analysis is imprecise, and we caution that our analysis is only indicative of the likely order of magnitude of net carbon sequestration under our maximum tree-planting scenario.

Works Cited

Photo © Kevin Kigger

Works Cited

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