Attachment 2

The impact of green space on heat and air pollution in urban communities:

A meta-narrative systematic review

MARCH 2015

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THE IMPACT OF GREEN SPACE ON HEAT AND AIR POLLUTION IN URBAN COMMUNITIES: A META-NARRATIVE SYSTEMATIC REVIEW

March 2015

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EXECUTIVE SUMMARY

It is widely understood that urban green spaces have a natural ability to filter pollution from the air and reduce local air and ground temperature. This report analyzed 102 peer-reviewed studies published over the past five years that explored the role of urban green space in providing cooling effects and reducing air pollution.

Not surprisingly, the report found that urban green spaces — from trees and parkettes to green roofs and large natural spaces — generally provide significant health benefits for residents and the community. It also found that these ecological benefits are directly related to the size, quality and density of the green space.

Why is it important to reduce urban heat effects and air pollution? It is estimated that tens of thousands of Canadians die prematurely each year due to acute air pollution and that high summer temperatures lead to increased illnesses, hospitalizations and deaths, especially among older adults. As the Canadian population ages and extreme heat waves become more common across the country, urban green spaces can provide essential, natural protection.

This report examined various types and scales of green space, and generally found that urban green space can provide cooler, cleaner air at the site, neighbourhood and city level. Emerging evidence also suggests that closely spaced and connected smaller green spaces can provide greater cooling effects to adjacent urban areas than large individual parks with open grass areas.

It found that the density and spatial configuration of an urban forest — the sum of all urban trees, shrubs, lawns and pervious soils located in an urban setting — clearly affect land surface temperatures in the city and that these elements are critical for improving urban air quality. In general, the research suggests that balancing urban forest density, particularly in areas with low green space density, would greatly improve both local and city-wide urban air quality.

Various plant species provide heat and pollution-mitigating capacities, and compact multi-layering of diverse plant species can help improve overall resiliency to drought, heat and pollution. Among plant types, trees have an exceptional ability to capture and filter multiple air pollutants, including ground-level ozone, sulphur dioxide, nitrogen oxides and particulate matter. Trees are also significantly associated with improved thermal comfort and relief from heat stress at the street level and neighbourhood scale, particularly during hot seasons and times of day.

The report also highlighted growing evidence of disproportionate heat- and air-pollution-related health burdens associated with unequal distribution of green space in urban neighbourhoods. Further investigation is needed regarding the prevalence of green space-related health inequalities, considering evidence in Canada that dense, low-income inner-city neighbourhoods are generally more vulnerable.

The report concludes with recommendations that include improving the quantity, quality and connectivity of green spaces; prioritizing green strategies for vulnerable urban areas; and integrating greening policies with broader health and land-use planning policies.

INTRODUCTION

Cities are amazing places. More than half the world's people live, work, rest and play in urban communities, and it is estimated that by the year 2030, three out of five people will call a city home (Fuller & Gaston, 2009; Smith & Guarnizo, 2009). In Canada, we are ahead of the curve. More than 81 per cent of us (over 27 million) live in urban areas. Between 2001 and 2006 the populations of Canada's six largest cities grew by almost eight per cent (Statistics Canada, 2011).

While cities bring us together, their rapid and unprecedented growth has also brought serious challenges, including environmental degradation, loss of natural habitat and species diversity, and increased human health risks associated with heat, noise, pollution and crowding. That means most children are growing up in environments with increasing pollution, intense heat and less access to diverse green spaces (Alberti & Marzluff, 2004; Cohen, Potcher & Matzarakis, 2012; Girardet, 1996; Gregg, Jones & Dawson, 2003; Grimm et al., 2008; Hough, 2004; Moore, Gould & Keary, 2003; Newman & Jennings, 2008). Given these challenges, there is a critical need to find ways to reduce health risks and maximize opportunities for well-being in all urban communities.

In response to this need, the David Suzuki Foundation has undertaken a systematic review of the evidence to understand how green spaces can help to reduce heat, improve air quality and support healthy livable urban communities. This report was commissioned by the David Suzuki Foundation in collaboration with the EcoHealth Ontario Research Working Group.

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REVIEW PURPOSE

We know urban green spaces such as parks and urban forests can help reduce heat and improve air quality. Recent systematic reviews have assessed a range of evidence to understand the benefits and value of urban trees, urban parks and the overall effectiveness of green space to reduce heat, ozone and ultraviolet (UV) radiation in urban areas (see Roy, Byrne & Pickering, 2012; Konijnendijk et al, 2013 and Bowler, Buyung-Ali, Knight & Pullin, 2010). Trees and plants have a varying capacity to capture and/or filter air pollution, improve air circulation and decrease ambient temperatures. Despite this, the vast array of study topics, methods, green space types and examined plant species make it difficult to determine the application of the evidence base in decision-making about community green space and health.

A synthesis of the evidence to better understand how different, types, scales and characteristics of urban greening can influnce heat and air polltuion, at both local and city-wide scales, is needed. This meta-narrative systemic review has been designed to respond to this need. The aim is to systematically identify and synthesize evidence on the specific green space settings and conditions that influence heat and air quality to answer the question:

What is the evidence that green space can support health in urban communities by reducing heat and air pollution?

To answer this question, several question sets were developed to explore specific green space settings and conditions that influence heat and air quality (see Table 1). This approach will help to clarify and address gaps identified in previous systematic reviews including the optimal amount, distribution and types of vegetation; differential impacts of green space scales; and, direct health impacts associated with reductions in heat and air pollution from greening (Bowler et al., 2010; Roy et al., 2012). The goal is to examine the state of the evidence, identify research gaps and make recommendations in support of healthy communities.

Table 1. Question sets to explore urban green space characteristics associated with heat and air pollution
1. Green space type and scale: What types of green space are associated with heat and air pollution mitigation (e.g., small green roof, large park, urban forest)? What studies, if any, compare different green space scales? What scales of impact have been documented (e.g., effect within green space area, effect on adjacent non-green areas, effect on entire city or region)? 2. Vegetation type: What specific types of vegetation are associated with heat and air pollution mitigation (e.g., plant types)? What studies, if any, compare the effect of different vegetation types? 3. Vegetation characteristics: What specific vegetation characteristics have been associated with heat and air pollution mitigation (e.g., vegetation density)? Do any studies compare the effect of different vegetation characteristics? 4. Modifying factors: What factors can modify the relationship between green space and heat or air quality (e.g., wind, season, time of day, surrounding infrastructure)? 5. Negative impacts: What, if any, negative impacts or trade-offs associated with green space are identified in the evidence base (e.g., BVOC exposure, reduced visibility near roadways)? 6. Health relevance: What health benefits have been directly associated with observed mitigation of heat or air pollution from green space?

BACKGROUND: HEAT, AIR QUALITY, GREEN SPACE AND HEALTH

HEAT AND HEALTH

Heat can be a killer. Data from around the world consistently show an association between increased daily temperatures and increased counts of deaths, illnesses and hospitalizations (Vutcovici, Goldberg & Valois, 2013). Older adults are particularly vulnerable. Heat-related health impacts (HRI) range from mild symptoms of fatigue and heatstroke to the worsening of preexisting illnesses, hypotension and death (Bernardo, Crane & Veenema, 2006; Bouchama & Knochel, 2002; Semenza, 1999; Simon, 1993).

A systematic review showed that increases in heat-related morbidity is positively associated with a growing aging population (Hajat & Kosatky, 2010). During the 2003 European heat wave, the majority of the estimated 40,000 extra deaths from extreme heat were among older adults (García-Herrera et al., 2010). The results from a review of 15 European cities showed that even though Mediterranean and North-Continental countries use different empiric thresholds to define a heat wave, they observed similar results for the 65- to 74-year-old populations across countries and strong and consistent temperature-mortality associations for those above the age of 75 (Oudin Åström, Bertil & Joacim 2011). Older adults are also more vulnerable due to social isolation (Hajat & Kosatky, 2010).

Living in an urban centre increases vulnerability to heat exposure. A review on heat-mortality relationships in cities found that in almost half of the locations studied, the risk of mortality increased between one percent and three per cent for every 1°C change in high temperature (Hajat & Kosatky, 2010). Urban settings experience higher temperatures than rural areas due a lack of vegetation, properties of urban materials that have a greater thermal storage capacity, geometry of urban areas, release of waste heat (e.g., from vehicles and buildings) and a city's size (Hajat & Kosatky, 2010). This is known as the urban heat island (UHI) effect. UHIs raise nighttime temperatures, leading to greater heat stress and limited relief from high temperatures (Kunkel et al., 1996; Harlan et al., 2006). As urban populations grow, the impact of the UHI effect becomes more dangerous. Globally, higher population densities were found to correlate with higher temperatures and greater thermal discomfort, particularly in low-income settings where there is the least economic capacity to adapt in the face of increasing extreme heat events (Hajat & Kosatky, 2010; Harlan, Brazel & Prashad, 2006).

In Canada, the number of seniors is expected to double by 2033 from about five million to 10 million (medium-growth scenario) with at least 75 per cent burdened by a chronic health condition (Sheets & Gallagher, 2013). A Toronto-based study found that, on average, for every one-degree C increase in maximum temperature, there was a 29 per cent increase in ambulance response calls for HRI (Bassil et al., 2010). For every one-degree increase in mean temperature, there was a 32 per cent increase in ambulance response calls for HRI (Bassil et al., 2010).

With a rapidly aging population and most Canadians living in cities, strategies to provide relief from heat and heat stress are important.

AIR QUALITY AND HEALTH

Air pollution is a complex soup of chemicals and molecules that most of us breathe daily. By volume, infants and children breathe far more air than adults. For example, a resting infant breathes in twice as much air as an adult. This means they are more exposed to local air pollutants during a period when their lungs are going through vulnerable stages of development (Landrigan et al., 1998). Excess air pollution can lead to airway inflammation and reduced lung function and can worsen health problems such as asthma, chronic obstructive pulmonary disease and cardiovascular disease (Shah & Balkhair, 2011).

Common air pollutants include particulate matter (PM), sulphur dioxide (SO2), ground-level ozone (O3), nitrogen dioxide (NO2) and carbon monoxide (CO). In 2005, 89 per cent of the world's population lived in areas where the World Health Organization Air Quality Guideline was exceeded (Brauer et al., 2012). Different air pollutants have different adverse health effects.

Coarse particulate matter (PM10) is emitted from residential heating sources and power plants, whereas fine PM2.5 comes from cars, utilities and wood burning (Shah & Balkhair, 2011). The World Health Organization estimates that PM contributes to approximately 800,000 premature deaths each year and 6.4 million lost years of healthy life in cities (Brauer, et al., 2012). The European Study of Cohorts for Air Pollution Effects (ESCAPE) review is the first multicentre study on the effects of long-term exposure to air pollution and mortality, and covers a study population of over 300,000 people in nine European countries. Most, but not all, studies showed statistically significant associations between PM2.5 and PM10 and all-cause or natural-cause mortality. PM2.5 was the pollutant most consistently associated with natural-cause mortality in the study (Beelen et al., 2014). Analysis also found that for every increase of five micrograms per cubic metre of PM2.5 pollution, the risk of lung cancer rose by 18 per cent, and for every increase of 10 micrograms per cubic metre in PM10 pollution, the risk increased by 22 per cent. The analysis did not find a threshold below which there was no risk (Raaschou-Nielsen et al., 2013)

A systematic review found exposure to sulphur dioxide (S02) was associated with pre-term births, while exposure to PM2.5 is associated with low birth weights, pre-term births and small for gestational age births. Ozone exposure may also have negative effects on birth weight and neurodevelopment, but its direct effect on pregnancy outcomes is unclear (Shah & Balkhair, 2011).

Canadian studies have reported significant associations between chronic exposure to traffic-related air pollution (specifically NO2) and an increased risk of ischemic heart disease (IHD) (Beckerman et al., 2012). Associations between ambient air pollution (nitrogen dioxide, sulphur dioxide, carbon monoxide and particulate matter with a diameter of 10 micrometres or less) and respiratory hospitalization, particularly for females up to age 14, have also been reported in Canada, as well as significant associations between exposures to elevated levels of air pollutants and increased resting blood pressure and lower ventilatory function (Luginaah et al., 2005; Cakmak et al., 2011).

In Canada, about 10 million people (32 per cent of the population) live in areas where they are exposed to traffic-related air pollution (Brauer, Reynolds & Hystad, 2013). Approximately 54 per cent of the Canadian population lives within 500 metres of a major road or highway, leading to a high prevalence of exposure (Brauer et al., 2013). Estimates suggest approximately 21,000 premature deaths are related to air pollution in Canada each year (Brauer et al., 2013).

According to a 2008 report by Canadian Medical Association, the number of premature deaths associated with chronic exposure to air pollution is expected to rise 83 per cent between 2008 and 2031 (an estimated 90,000 deaths from the acute effects of air pollution and an estimated 710,000 deaths due to long-term exposure to air pollution), with Quebec and Ontario bearing the largest proportion of acute premature deaths (Canadian Medical Association, 2008).

Strategies to reduce local air pollution and improve air quality are important to the health of urban communities.

UNDERSTANDING THE ROLE OF GREEN SPACE IN PROTECTING HEALTHY COMMUNITIES

As summarized, strong evidence documents the harmful health effects of extreme heat and air pollution. A large and growing evidence base also shows how green space can help to reduce heat and combat air pollution in urban settings. A comprehensive systematic review by Bowler et al. in 2010 assessed the effectiveness of greening strategies to reduce exposure to urban heat islands, ground-level ozone, volatile organic compounds (VOCs) and nitrogen oxides (NOx). They assessed 212 studies published up to the year 2009. They found that on average the daytime air temperature of parks were an estimated 1°C cooler than built-up (non-green) urban areas (Bowler et al., 2010). Overall, the review found that greening interventions might be effective to help mitigate urban heat islands and improve air quality but that evaluation of biogenic VOC emissions from certain plants (a precursor to ground-level ozone) should be included in greening strategies.

Bowler et al. (2010) also identified a number of gaps in the literature, which include a lack of data on the direct health effects of green space as a result of its influence on heat or air quality, a lack of studies on the impact of greening on human heat stress or thermal comfort, a lack of studies on the impact of urban green space on nearby non-green areas, and lack of data on the optimal size, distribution and characteristics of green space.

Figure 1 depicts a basic conceptual overview of the evidence base on green space, heat, air quality and health. Strong evidence on the relationship between heat and air pollution and health has been documented (label a). There is also a large and growing evidence base on the relationship between green space and health in general (label b) (see systematic reviews by Lachowycz & Jones, 2011, and Lee & Maheswaran, 2011). Evidence on the influence of green space on heat and air pollution mitigation is extensive and broad, but there is a gap in understanding of how specific settings and green space characteristics can maximize these benefits (label c). Lastly, studies that examine the relationship of all three spheres together (i.e., health benefits that have been directly associated with observed mitigation of heat or air pollution from green space) are lacking (label d).

This review focuses on evidence published since the Bowler et al. systematic review and explores the state of recent evidence in addressing gaps c and d of figure 1.

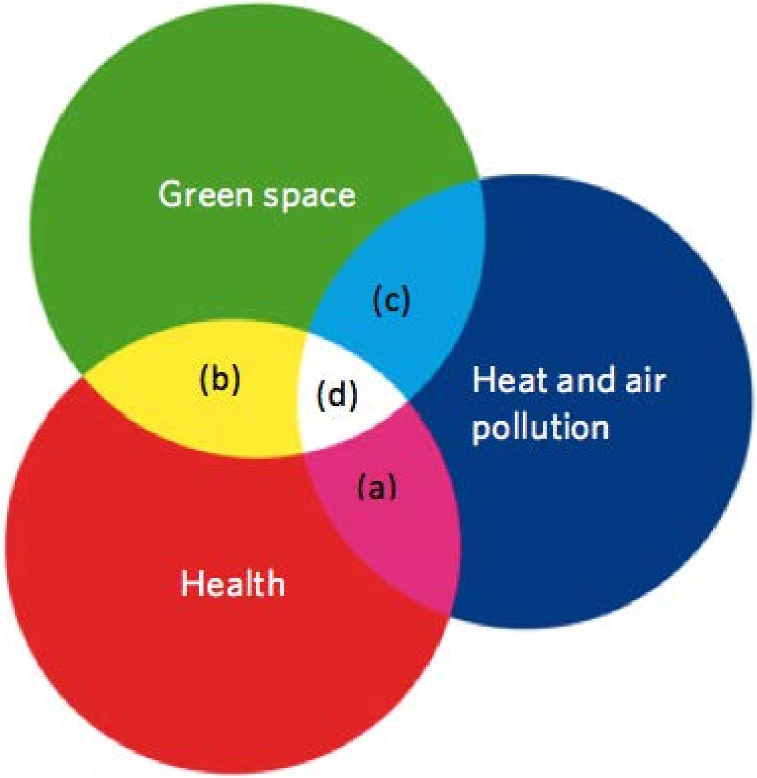


Figure 1. The data gap: understanding the evidence base on green space, heat, air quality and health
(a) Strong evidence base on the relationship between heat and health and air pollution and health; (b) Large and growing evidence base on the relationship between green space and health in general; (c) Growing evidence base on the relationship between green space heat and air quality but gaps regarding the specific settings and greening characteristics to maximize benefits; (d) Data gap: documented health impacts as a result of greening strategies that reduce urban heat and air pollution.

METHOD

A meta-narrative systematic review was used to synthesize evidence on urban green space, heat and air quality. The review method is designed to support complex policy decisions, where the evidence base includes many different disciplines and study designs (Barnett-Page & Thomas, 2009). This review process is ideal when there is a need to examine a range of methods for studying an issue (as opposed to a single intervention), interpret and create an account of different streams of evidence and create an overarching meta-summary of the findings (see Gough, Thomas & Oliver, 2012). The approach is well-suited to evidence reviews on human health and the environment, where there is typically a complex, diverse and interdisciplinary evidence base (see Greenhalgh et al. 2005).

Six standard review stages were completed to identify and consolidate the broad evidence base on urban green space, heat and air quality (see Wong et al., 2013):

1) scoping (July 2014)
2) systematic database searching (final database search completed October 21, 2014)
3) article appraisal and quality assessment (October 2014)
4) data extraction (November 2014)
5) data analysis and synthesis (November 2014)
6) integration and results reporting (December 2014 to January 2015)

Landmark papers and systematic reviews identified by members of the EcoHealth Ontario Research Working Group were explored to develop the search protocol. (See Table 2 for list of scoping papers and Table 3 for search protocol.) The electronic database search was limited to studies published between 2009 and October 2014 (since the publication of the review by Bowler et al., 2010).

Studies in climates relevant to Canada were included in the review. For example, studies from warm-temperate climates are relevant to summer condition in many Canadian provinces. Using the Köppen Climate Classification System, studies from locations in Warm Temperate Climates (type C), Snow Climates (type D) and Polar Climates (Type E) were included in the review (Kottek et al., 2006). Studies from Equatorial Climates (Type A) and Arid Climates (Type B) were excluded. (See appendix D for glossary of climate classifications.)

The electronic database search returned 1,005 unique articles. Two reviewers independently appraised the articles, by title and abstract, and rejected articles that failed to meet the inclusion criteria. Disputed articles were rejected. The full text of 95 accepted articles was retrieved and appraised for meeting the quality criteria. The reference lists of 88 accepted articles were hand searched to identify an additional 14 relevant studies. A total of 102 studies were accepted into the review. (See Figure 2 for demonstration of selection process.)

Two reviewers independently applied a standard data-extraction form to 20 per cent of the articles to test inter-rater reliability. Data extraction was then completed for all remaining studies.[1] Variables such as date, city, climate, green space type and method for each article were recorded using the statistical software program (SPSS), and each article's findings, limitations and implications were also explored

1 Raw inter-rater concordance (the degree of agreement between reviewers) averaged 93 per cent, with a range of 89.4 per cent to 100 per cent across variables.

and documented. The contribution of each study to each of the question sets was examined and a synthesis of findings was completed and summarized in a narrative report.

Table 2. Reviews and studies examined during scoping phase
Bowler, D., Buyung-Ali, L., Knight, T., & Pullin, A. S. (2010). How effective is "greening" of urban areas in reducing human exposure to ground level ozone concentrations, UV exposure and the "urban heat island effect". Environmental Evidence: www. Environmental evidence.org/SR41. Html
Depietri, Y., Renaud, F. G., & Kallis, G. (2012). Heat waves and floods in urban areas: a policy-oriented review of ecosystem services. Sustainability science, 7(1), 95-107
Escobedo, F. J., Kroeger, T., & Wagner, J. E. (2011). Urban forests and pollution mitigation: analyzing ecosystem services and disservices. Environmental Pollution, 159(8), 2078-2087
Haase, D., Larondelle, N., Andersson, E., Artmann, M., Borgström, S., Breuste, J., ... & Elmqvist, T. (2014). A quantitative review of urban ecosystem service assessments: Concepts, models, and implementation. Ambio, 43(4), 413-433
Konijnendijk, C. C., Annerstedt, M., Nielsen, A. B., & Maruthaveeran, S. (2013). Benefits of urban parks: a systematic review. A report for IPFRA. IFPRA
Nowak, D.J., Hirabayashi S., Bodine A, Greenfield, E., (2014) Tree and forest effects on air quality and human health in the United States. Environmental Pollution 193 119e129
Rowe, D. B. (2011). Green roofs as a means of pollution abatement. Environmental Pollution, 159(8), 2100-2110 *Roy, S., Byrne, J., & Pickering, C. (2012). A systematic quantitative review of urban tree benefits, costs, and assessment methods across cities in different climatic zones. Urban Forestry & Urban Greening, 11(4), 351-363.*

Figure 2. Demonstration of article selection process and results

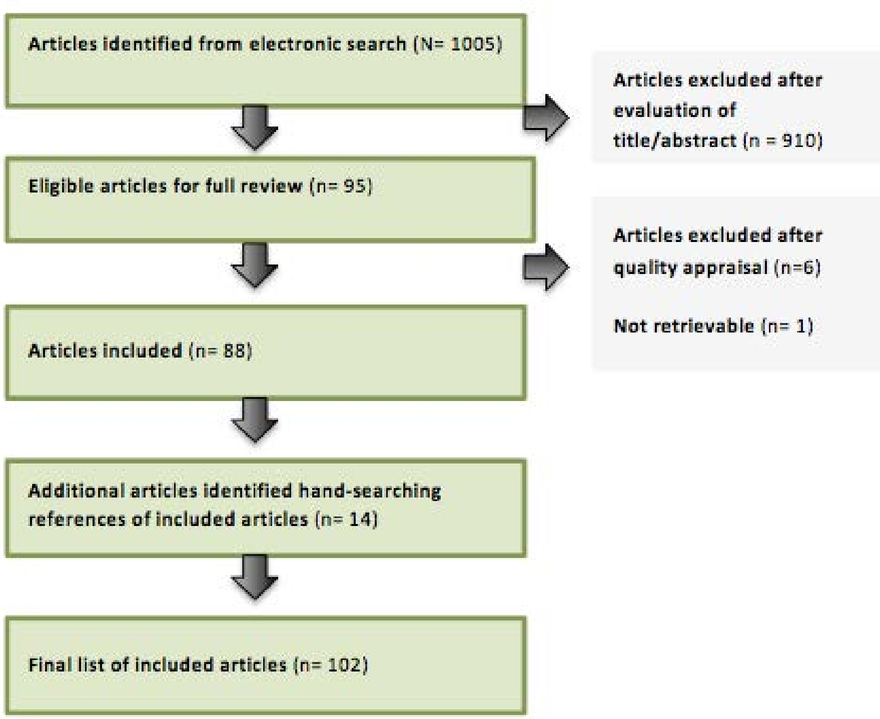


Table 3. Search protocol and selection criteria	
Inclusion criteria	Peer-reviewed empirical studies on the relationship between (a) urban green space and air quality or (b) urban green space and heat that are; · Published between the years 2009 and 2014; · Set in a "Moist Subtropical Mid-Latitude Climates" (type C) or a "Moist Continental Mid-latitude Climates" (type D) or a "Polar Climate" (Type E) according to the Köppen Climate Classification System (Kottek et al. 2006).
Exclusion criteria	· Non-empirical studies (theoretical or narrative articles that do not present original empirical data); · Papers written in languages other than English or French; · Studies focusing on green space in a rural context; · Studies reporting the impact of green space on direct health outcomes (physical, mental or social health of individuals or populations) with no original data on air pollution or heat mitigation; · Papers published before the year 2009; · Studies from Equatorial (Tropical) Climates (Type A) and Arid Climates (Dry) (Type B) according to the Köppen Climate Classification System (Kottek et al. 2006).
Key words	green space OR park* OR garden* OR field* OR green trail OR living wall OR green roof* OR green corridor OR vegetation OR tree* OR woods OR forest* OR green wall OR plant* OR urban forest OR meadow OR ecosystem service OR naturalized area OR grass OR open space OR urban greening OR urban cool island AND heat OR urban heat island OR heat wave OR temperature OR heat mitigation OR air quality OR air pollution OR volatile organic compounds OR biogenic volatile organic compounds OR nitrogen dioxide OR particulate matter OR carbon monoxide OR criteria pollutants OR ozone OR sulfur dioxide OR heavy metal AND urban OR peri-urban OR suburban OR city OR town
Electronic databases (n= 11)	GreenFILE @ EBSCO; PubMed; Ecology Abstracts @ProQuest; Environment Abstracts@ ProQuest; Plant Science@ProQuest, Pollution Abstracts@ProQuest; Sustainability Science Abstracts@ProQuest, TOXLINE@ProQuest; MEDLINE @ OVID; Embase@OVID; Google Scholar
Quality criteria	This review draws on diverse studies, methods and disciplines. As a result, no single set of quality criteria could be applied, since each study would have to be assessed in its particular research tradition (see Wong et al, 2013). Articles were appraised and accepted if they met the three following quality criteria (see Hannes, 2011, Cochrane Collaboration Qualitative Methods Group): · Credibility: evidence of outside auditors or participants validating findings, such as peer debriefing or independent analysis of data by more than one researcher; · Transferability: details of the study context, to enable reviewers to evaluate which target groups or context the study covers; and, · Dependability: clear documentation of methods with third-party validation or peer review.

FINDINGS

OVERVIEW OF STUDIES

There is considerable research interest regarding the influence of urban green space on heat and air quality. Database searches identified 102 relevant peer-reviewed studies published between 2009 and October 2014. Figure 3 shows the annual distribution of studies by research topic. It shows an even distribution among studies focused on heat mitigation (52 per cent) and air pollution mitigation (45 per cent). (Three per cent of studies focused on both heat and air pollution mitigation.) Almost 90 per cent of the research is made up of observational studies. Among the observational studies, almost 50 per cent use modelling methods, followed by remote sensing (26 per cent), ground-level data collection (21 per cent), cross-sectional studies (three per cent) and longitudinal studies (one per cent). Five studies apply experimental approaches and the remaining six studies are reviews.

Many of the recently published studies directly address data gaps identified in previous reviews (Bowler et al., 2010; Roy et al. 2012). This includes the comparison of amounts, distribution and types of vegetation (e.g., Chen, Yao, Sun, & Chen, 2014; Perini & Magliocco 2014); differential impacts of green space scales (e.g., Cohen et al., 2012); and, direct health impacts associated with heat and air pollution mitigation from greening (e.g., Alonso et al., 2011; Nowak et al., 2014). The data set also includes first-of-its-kind studies, such as the cooling effects of parks on surrounding air and surface temperatures (see Feyisa et al., 2014), the impact of greening on individual and household-level exposure to air pollution (see Dadvand et al., 2012 and Maher et al., 2013), the impact of urban green spaces on human thermal comfort in winter (see Cohen et al., 2012), differential air quality impacts of roadside plants (see Weber, Haase & Franck, 2014) and the effects of trees on air quality and human health at a national level (see Nowak et al., 2014).

A total of 27 countries are represented, with the majority of research set in the United States (26.3 per cent), followed by China (12.6 per cent), Japan (7.8 per cent), England (7.4 per cent), Italy (6.3 per cent), Greece (4.2 per cent), and Germany (4.2 per cent). Only two studies are from Canada. Climate settings were categorized using the Köppen climate classifications (Kottek et al., 2006).[2] Almost half of the research is set in "warm temperate fully humid climates" (Cf) such as London, England, and Beijing, China (49.5 per cent), followed by "warm temperate dry summer climates" (Cs) such as Athens, Greece (25.8 per cent); "snow climate, fully humid" (Df) such as Toronto, Canada (17.2 per cent); "warm temperate climate with dry winter" (Cw) such as Hong Kong, China (5.2 per cent) and "snow climate with dry winter" (Dw) such as Seoul, Korea (2.2 per cent).

2 Studies set in tropical or arid climates were excluded from this review

Figure 3. Research focus by year of publication

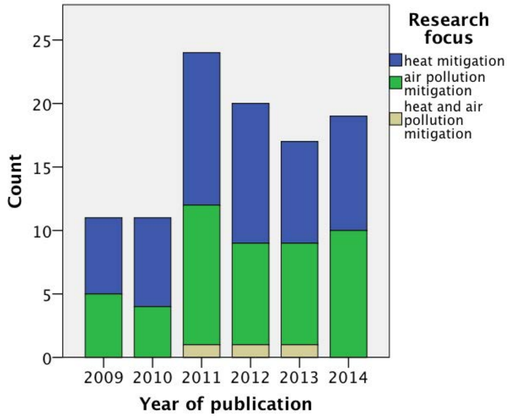
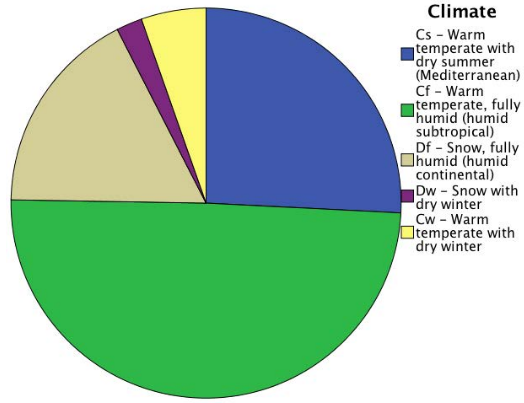


Figure 4. Distribution of studies by climate settings



OVERVIEW OF THE RELATIONSHIP BETWEEN GREENSPACE, HEAT AND AIR QUALITY

Among the identified studies on green space and air pollution, 92 per cent reported pollution mitigating effects (Figure 5). Among studies on heat mitigation, 98 per cent reported urban cooling effects associated with green space (Figure 6). Five studies did not report beneficial effects of green space. Three studies reported increased air pollution resulting from BVOC emissions from green space (Curtis et al., 2014; Bao et al., 2010; Ren, et. al., (2014). One study found that street canyon vegetation increased levels of air pollution within the canyon (Vos, Maiheu, Vankerkom & Janssen, 2013), and one study of a large park in Athens, Greece, reported no observed cooling effect (Zoulia, Santamouris & Dimoudi, 2009).

Figure 5. Studies reporting pollution mitigation from green space

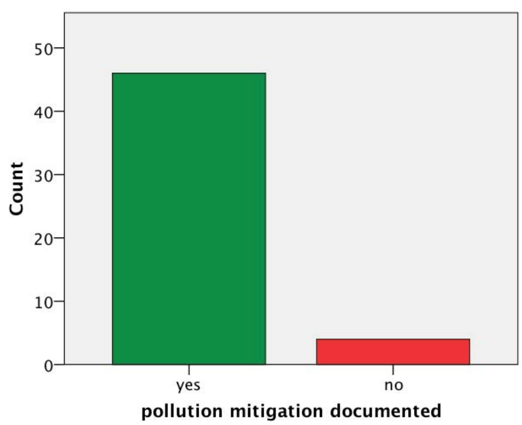
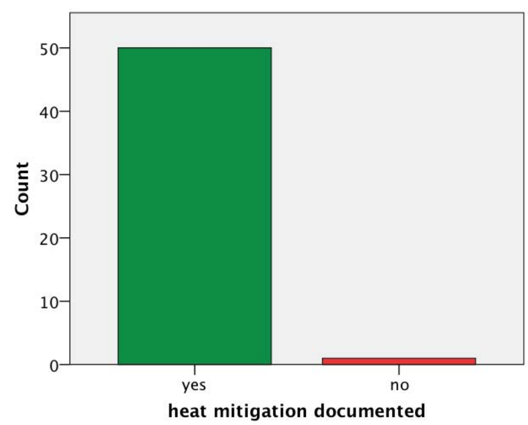


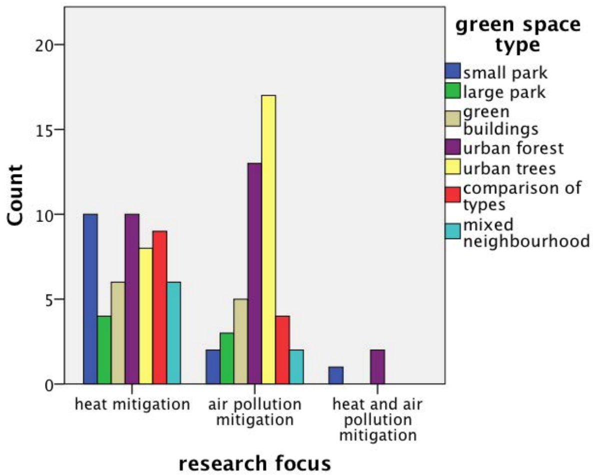
Figure 6. Studies reporting heat mitigation from green space



STUDY VARIABLES

Six different urban green space types were identified in relationship to heat and air pollution mitigation. These are: 1) green buildings, 2) small parks, 3) urban trees, 4) mixed neighbourhood green space, 5) large parks, and 6) urban forests. Figure 7 shows the distribution of green space types examined. Among studies on air pollution and green space, studies on urban trees and urban forests predominate the literature, with only four studies comparing the effects of different green space types or scales. For studies on heat mitigation, research is more evenly distributed among the different green space types and more studies draw comparisons among them.

Figure 7. Distribution of green space types among studies on heat mitigation and air pollution mitigation



In terms of plant types, the effects of trees were examined the most, making up almost half of the studies reviewed, followed by comparisons of mixed vegetation (table 4).

Among the different characteristics of urban green space found to influence heat, green space density was examined the most (n=39), followed by patch size (n=9), patch shape (n=9) and spatial configuration (where it was located in an urban setting) (n=4).

Among the modifying variables identified for affecting the relationship between green space and heat, the surrounding built environment was examined the most (n= 24), followed by season (n=12), temperature (n=14), wind (n=9) and precipitation/irrigation (n=3). The only main trade-off identified in the literature is the cost associated with greening.

The main characteristics explored in relation to green space and air quality are green space density (n=32), plant height (n= 8) and plant leaf characteristics (n=8). Modifying variables identified for affecting the relationship between green space and air quality are wind (n=16), patterns of the surrounding built environment (n=11), season (n=8), air pollution levels (n=5), precipitation (n=3) and location of vegetation (n=3). Particulate matter was the main air pollutant studied (n=23), followed by N02 (n=18), O3 (n=11), SO2 (n=4), BVOC (n=4) and airborne heavy metals (n=1). Two main negative impacts were identified in the literature associated with urban greening: 1) increased BVOC emissions and 2) increased localized air pollution in street canyons. Exploration of direct health impacts was limited to mortality rates, respiratory health and health inequalities related to green space distribution.

Table 4. Distribution of plant types examined

Vegetation type	Studies on heat mitigation (count)	Studies on air pollution mitigation (count)
Tree	13	24
Grass	1	1
Shrubs	0	0
Mixed	8	3
Comparison of types	17	9

TYPES OF GREEN SPACES FOUND TO INFLUENCE HEAT AND AIR QUALITY

Among the studies reviewed, all types of green space, ranging from small green walls to large-scale urban forests, were positively associated with both cooling effects and improvements to air quality. The following sections describe the overall findings for each type of green space as well as comparisons where they exist.

Green buildings: Overview

In this review, green buildings refer to urban buildings with an exterior vegetated roof or wall. Green walls may serve as a significant intervention for mitigating heat stress and urban heat islands but they are underexplored in the literature. The combined benefits of green roof heat mitigation and pollution mitigation need to be taken into consideration to assess the overall cost/benefit of green roofs compared to other cool roof alternatives. While green roofs may not be as effective as street trees in improving air quality, they may be a useful alternative in areas where there is limited capacity for tree-planting (Speak, Rothwell, Lindley & Smith, 2012; Baik, Kwak, Park & Ryu, 2012).

Green buildings and heat

Since 2009, six studies on the relationship between green buildings and heat were identified. All six studies reported positive cooling effects from green building interventions.

Cooling effects of green walls were documented in two experimental studies of living walls, both in warm temperate fully humid climates (Cf). In Sheffield, U.K., a controlled experiment by Cameron, Taylor and Emmett (2014) analyzed the effect of living walls on adjacent air temperature compared to brick walls. The "living walls" provided local cooling and significantly reduced both wall surface and adjacent air temperatures. During the warmest periods, air temperatures were 3°C cooler in the presence of the vegetated wall and surface temperatures behind the vegetation were as much as 9.9°C cooler than the brick wall, even though both walls were irrigated at the same rate. A similar study by Koyama et al. (2013) in Nagoya, Japan, found that living walls also cooled wall surface temperatures and showed potential to mitigate urban heat island effects by blocking the long wave radiation from the walls into the environment at night. While research on the impact of green walls is still emerging, these results suggest that vegetated building walls can mitigate urban heat island effects and provide considerable relief from heat stress, particularly in areas where ground space for vegetation is limited.

Green roofs can help to combat urban heat islands through the combined effect of evapotranspiration of plants and the surface albedo (Susca, Gaffin & Dell'Osso, 2011; Smith & Roebber 2011). However, there is some debate over whether green roofs are as effective as simpler and less expensive cool (high albedo) roofing systems that reflect heat during the day. Four studies on green roofs across three different climates generally show that green roofs provide some heat mitigation but that the effects are equal to or less than cooling effects achieved from more simple cool roof surfaces (such as white high-albedo roofs). A city-scale modelling study in Chicago (Df climate) by Smith and Roebber (2011) explored the impact of green roofs on the urban heat island in summer and estimated that the green rooftops would reduce air temperatures in the urban environment (by as much as 3°C). Similarly, an experimental study by Susca et al. (2011) compared the effects of a white and green roof during the summer in New York City (Df climate) and reported that during the hottest period of the day, the surface temperature of the green roof was almost one to eight K lower than the white roof. However, in a warm temperate fully humid climate (Cf) of Melbourne, Australia, an experimental comparison of four green roofs (steel, white, vegetated and soil-only roofs) found that the high albedo rooftop, if combined with insulation, provided the greatest overall benefit in terms of urban heat mitigation (Coutts, Daly, Beringer & Tapper, 2013). The differences in findings could be the result of many factors such as study method, setting, vegetation type or climate.

Studies on surface temperature can only provide data relating to urban heat islands but do not provide information about the effects on air temperature, which is important for understanding the effect of green space on human exposure to heat and thermal comfort. For example, one study on the impact of green roofs on thermal comfort in the cities of Barcelona, Palermo and Cairo (Cs) found that only well-irrigated green roofs provided cooling (Zinzi & Agnoli, 2012). Increases in moisture resulting from evapotranspiration lead to only marginal cooling when apparent temperatures are considered, therefore modelled estimates of green roof performance are difficult to assess (Smith & Roebber, 2011). However, green roofs provide more benefits than heat mitigation and cost/benefits comparisons to "cool roof" systems alone may underestimate the value of green roofs in cities.

Green buildings and air quality
Among the studies on green roofs and air quality is an extensive review by Rowe, 2011, which found air pollution removal through the intensive application of green roofs is comparable to mitigation effects of urban forests. For example, adoption of green roofs by 20 per cent of "ready" buildings in Washington, D.C., was estimated to remove the same amount of air pollution as 17,000 street trees, and an estimated 20 per cent conversion of all industrial and commercial roofs to green roofs in Detroit, Michigan, would remove over 800,000 kilograms (889 tonnes) per year of NO2 (Rowe, 2011).

A more recent modelling study in Washington, D.C., reported that increasing the scale of green roofs to 20 per cent of "ready" roofs would result in an estimated uptake of 38,000 kilograms of NO2 per year and 513,000 kilograms per year using experimental metric (Niu, Clark, Zhou & Adriaens, 2010). In Manchester, England, ground-level data on the impact of two green roofs were used to estimate the PM mitigation from a 50-hectare green roof strategy. They estimate that 0.21 tonnes or 2.3 per cent of PM10 levels would be removed annually (Speak et al., 2012).

The first-known study of green roofs on air quality in a street canyon found that the cool air produced from the roof flows into the canyon and improves air flow and air quality near the road. The study found that air cooling from green roofs causes air quality near the road to improve by strengthening street canyon flow and enhancing pollutant dispersion when compared with the no-cooling case. Among the eight roof experiments, the average pollutant concentration (NO and NO2) was reduced by 49 per cent from 247 to 126 ppb with the largest reduction being 57 per cent (Baik et al., 2012).

Small urban parks: Overview
For this review, a park was considered small if it was reported to be less than one hectare in size or referred to as "small". The range of studies examined in this review report significant cooling effects of small parks in all climates examined. The intensity of park cool island effects (PCIs) may

be confounded by many variables, particularly the surrounding density of non-green urban areas. In general, modelling for PCI is expected to be underestimated for very small parks (Cao, Onishi, Chen & Imura, 2010). Despite the possible confounders, a large cross-sectional study reported that longer and frequent visits to small urban parks were significantly associated with relief from heat stress. Research on the impact of small parks on air quality is limited; however, emerging evidence has documented differences in the air quality of urban parks according to the socioeconomic status of neighbourhoods. This suggests possible inequities related to green space quality that may affect urban health inequalities.

Small urban parks and heat

The effects of small green urban areas on heat have been less explored in comparison to larger parks and urban forests (Oliveira, Andrade, & Vaz, 2011). A previous larger review reported that, on average, daytime air temperatures of parks were an estimated 1°C cooler than built-up non-green urban areas (Bowler et al., 2010). Among the 11 identified studies published in the past five years, all reported cooling effects (ranging between 4 to 7°C) compared to adjacent non-green areas.

Overall, the findings show that in all climates studied, small parks can provide a park cool island (PCI) that provides relief from heat stress. The degree of cooling was influenced by variables such as local temperature, plant type and density, wind and green patch size (Armson, Stringer, & Ennos, 2012; Cao et al., 2010; Feyisa et al., 2014; Fintikakis et al., 2011; Froehlich & Matzarakis, 2013; Gaitani et al., 2011; Konijnendijk et al., 2013; Lafortezza, Carrus, Sanesi, & Davies, 2009; Oliveira et al., 2011; Onishi et al., 2010; and Vidrih & Medved, 2013).

Studies set in warm temperate dry summer climates (Cs) found that, on average, air temperatures of parks are 2°C cooler and up to 3°C cooler at peak summer temperature with surface temperatures from 6 to 8°C cooler (Fintikakis et al., 2011; Gaitani et al., 2011). One study reported that air temperatures within the park were significantly cooler than both shaded and sunny non-green areas, with the greatest difference reaching a maximum of 6.9°C (Oliviera et al., 2011). A study of 21 parks in the warm temperate dry winter climate (Cw) of Addis Ababa reported an average park cooling effect of 3.93°C (ranging from 0.11 to 6.72°C) (Feyisa et al. 2014). In warm temperate humid climates (Cf), local air temperature cooling in parks compared to non-green areas ranged from 4.8°C in Ljubljana, Slovenia, to 5 to 7°C in Manchester, England (Vidrih & Medved, 2013; Armson et al., 2012).

These cooling effects contribute significantly to the well-being and quality of life of life of urban citizens by reducing heat stress. A cross-sectional study of 800 people reported that longer and frequent visits to small urban parks are significantly associated with improvements to perceived well-being and relief from thermal discomfort during periods of heat stress (Lafortezza et al., 2009).

Among the studies identified, three respond to a research gap identified by Bowler et al. (2010) regarding the cooling impact of small parks on adjacent non-green areas. A study of 21 urban parks in a warm temperate dry winter climate (Cw) found that the mean surface temperature from the edge of each park to adjacent areas outside of the park was significantly influenced by park size, vegetation density, park shape and distance from park, and that the maximum cooling distance from a park was 224 metres (Feyisa et al., 2014). Similarly, in a warm temperate fully humid climate (Cf) a study of 92 parks on the surface temperature of the surrounding 500-metre area found the cooling effect depended on park size, seasonal temperature, vegetation density and park shape, with greater size, density and complex shapes contributing to greater cooling distances (Cao et al., 2010). These emerging data may help to guide planning for optimal distances between small urban green spaces to provide maximum cooling to urban communities (Doick, Peace & Hutchings, 2014).

Small urban parks and air quality

Only three studies were identified on the impact of small urban parks on air pollution. A recent systematic review found that although the impacts of urban trees have been studied extensively, research specifically on urban parks has been limited. In general there appears to be a dearth of research in this area and there is currently only moderate evidence that urban parks mitigate SOx, NOx, CO and particulate matter (Konijnendijk et al., 2013; Yin et al., 2011).

A unique cross-sectional study on the relationship between green space, air pollution and health inequality was identified (Su, Jerrett, de Nazelle, & Wolch, 2011). The study explored pollution levels of Los Angeles parks according to neighbourhood socioeconomic status. The study found that exposures to NO2 and PM2.5 were significantly and systematically higher for the lower socioeconomic and higher minority population neighbourhoods. This suggests that possible inequities related to green space distribution and neighbourhood quality might affect urban health inequalities.

Urban trees: Overview

In this review, urban trees include stands of trees found in urban spaces other than parks or forested areas. They can include street trees, trees in public community areas other than parks and trees in backyards, commercial areas and other private properties (Roy et al. 2012). Evidence from this review and earlier reviews suggests that even single trees are critical for reducing heat stress and related health risks, buffering the urban heat island and cleaning the urban air. Ensuring equal distribution of trees in urban neighbourhoods may be particularly important for reducing health inequalities. However, in the case of street canyons, trees in some cases could be detrimental and increase localized exposure to traffic emissions and other air pollution due to the confluence of many variables such as wind speed, building heights and traffic levels. Therefore, many authors suggest case-by-case modelling of tree-planting in street canyons to maximize benefits and minimize negative impacts.

Urban trees and heat

Eight studies on the effects of urban trees on heat were identified. Five studies explore thermal comfort, two studies explore urban heat island and one is a review of the literature. All studies report heat mitigation from urban trees.

Tree shade is significantly associated with improved thermal comfort and relief from heat stress at the street level and neighbourhood scale (Hwang, Lin & Matzarakis, 2011; Lin, Matzarakis & Hwang, 2010; Meier & Scherer, 2012; Park, Hagishima, Tanimoto & Narita, 2012; Shashua-Bar, Tsiros & Hoffman, 2012; and Sung, 2013). Experimental field data collected in summer in a warm temperate fully humid climate (Cf) found that trees with dense shade along a sidewalk significantly decreased the mean radiant temperature, radiation flux and thereby the thermal comfort of urban streets (Park et al., 2012).

Both objective and subjective measures of thermal comfort found it is improved by tree shade during spring, summer and autumn but not winter when shade is not needed (Lin et al., 2010; Hwang et al., 2011). Ground-level data collected in Berlin (Df climate) found that even in distinct hot and dry periods, mature trees remained relatively cool in contrast to non-green impervious surfaces (Meier & Scherer, 2012). These findings are supported by an earlier review on urban trees and heat, where all studies reviewed reported a cooling effect on urban climate mainly through shade provision, reduction of air temperature and the mitigation heat island effects (Roy et al., 2012).

Studies suggest that urban trees have a superior ability to provide thermal comfort and relief from heat (Hwang et al., 2011; Lin et al., 2010; Lynn et al., 2009; Meier & Scherer, 2012; Park et al., 2012; and Shashua-Bar et al., 2012). For example, a comparison of natural and man-made shading scenarios in a warm temperate dry summer climate (Cs) showed that all types of shade could reduce the number of heat stress hours in the day but that trees with dense canopy coverage were the best for decreasing air temperatures, particularly on the hottest days (Shashua-Bar et al., 2012). Although other shade structures improved thermal comfort, they did not provide evapotranspirative cooling. Therefore, trees are likely the most beneficial shade intervention due to their ability to affect both the microclimate through their cooling effect and thermal comfort through shade provision.

A similar investigation in New York City (Df climate) by Lynn et al. (2009) showed that increased heat reflecting surfaces (increasing surface albedo) to combat urban heat island may be detrimental due to increased thermal stress at the street level from reflected solar radiation and emitted thermal radiation from the street. The presence of shade trees is shown to reduce the energy load on a person by blocking downward solar radiation and thereby reducing the amount of reflected shortwave radiation from the surface. Upward thermal radiation from the surface is also reduced in this case because the surface under the tree is also cooler than indirect sunlight. The implication is that although trees may be less effective than other strategies in reducing overall urban air temperature, trees provide the best combination of reducing late-day surface temperature and midday radiation stress on a person at street level (Lynn et al., 2009).

At the broader neighbourhood scale, ground-level data in the warm temperate fully humid climate (Cf) of Texas showed that neighbourhoods with tree protection policies reported average land surface temperatures that were consistently cooler (between 1.5 and 3.9°C) than those of the control neighbourhoods that were otherwise physically and socioeconomically similar (Sung et al., 2013).

Emerging evidence shows some neighbourhoods may be disproportionality burdened by heat-related health risks associated with a lack of urban trees. A cross-sectional study of multiple cities in the United States reported significant differences in the distribution of urban trees according to "ethno-racial" background. Living in areas with less tree cover was associated with greater inequality in terms of heat-related health risk. Adjustment for home ownership and income level did not substantially alter these results. However, adjustment for population density reduced the effects, suggesting a mediating or confounding role. Other possible confounding factors were not accounted for, such as unequal access to air conditioning and social isolation. However, the results suggest that health disparities related to tree cover among city neighbourhoods can exacerbate health inequalities (Jesdale, Morello-Frosch & Cushing, 2013).

Urban trees and air quality

Trees are well-known for removing a number of air-borne pollutants, including ozone, sulphur dioxide, nitrogen dioxide and particulate matter (Grundstrom & Pleijel, 2014; Harris & Manning, 2010; Kocic, Spasic, Urosevic & Tomasevic, 2014; and Roy et al., 2012). A large body of evidence documents the exceptional ability of trees to improve air quality at local sites and across cities (Nowak et al., 2014).

This section focuses on some of the challenges in the research associated with trees and air quality. A new study suggests that the air quality effects of trees may be different in northern climates like Canada. Setala, Viippola, Rantalainen, Pennanen and Yli-Pelkonen (2013) collected ground-level data from 20 sites to examine seasonal difference of trees in northern conditions (in urban areas of Finland, Df climate). They found that the ability of trees to remove air pollutants is minor in northern climates. They report a decrease in PM and NO2 concentrations compared to non-treed areas, but the difference was not significant. They also found that the relative effect of tree-covered areas on air pollution concentrations did not differ between winter and summer, challenging the notion that leaves are the main mechanism for air-quality improvement in urban settings. The reason for the reduced pollutant concentrations in tree-covered areas during winter remains unexplained but these findings contradict modelled predictions of significant removal of air pollution from trees. Their findings may be the result of differences in climate, tree species or study methods and should be explored further (Setala et al., 2013).

There is evidence that some trees emit BVOCs and can contribute to an increase in ground-level ozone when mixed with NO2 in the presence of sunlight. Harris and Manning (2010) found that when ambient NO2 levels are high, tree canopies will act as NO2 sinks, but when ambient levels are low, canopies will act as indirect sources of NO2. Some trees are high emitters of BVOCs and it is suggested that tree selection, particularly in high-traffic areas, is important for air-quality improvements. Curtis et al. (2014) assessed nine urban tree species for air-quality impacts in the warm temperate fully humid climate of Denver (Cf). They estimated that planting one million low-emitting tree species (sugar maple, Ohio buckeye, northern hackberry, Turkish hazelnut, London planetree, American basswood, littleleaf linden, Valley Forge elm, and Japanese zelkova) will prevent between 300,000 kilograms and 1.1 million kilograms in VOC emissions, compared to planting the same number of high-BVOC-emitting Kermes and English oak tree species, respectively. This reduction in VOC emission is estimated to be equivalent to removing almost 500,000 cars from inner city traffic (Curtis et al., 2014). Compared to other potential urban tree species, the selected trees had BVOC emission rates that were one-tenth to one-hundredth the rates of high-BVOC emitting trees.

Trees as sources of pollution represent a complex trade-off, but most studies that examined BVOC emissions find that proper species and site-specific management would lead to air-quality benefits that would outweigh negative impacts associated with effects of BVOCs (Harris & Manning, 2010; Ren et al., 2014).

The first known study to examine the effectiveness of street trees as a barrier to PM10 exposure at the household level found that the temporary installation of a curbside line of young birch trees resulted in more than a 50 per cent reduction in measured PM levels inside the houses compared to controls

(Maher et al., 2013). This result adds support to the findings by Dadvand et al. (2012) that increased neighbourhood green space is significantly associated with reduced household PM exposure. The early findings suggest that roadside tree barriers, particularly near vulnerable areas such as schools and hospitals, could reduce local exposures However, a number of studies suggest that, depending on the location, this strategy could increase air pollution hot spots.

Over half of the studies on urban trees and air quality in this review (n=11) focus on the impacts of street trees. Pollution mitigation along roadsides is highly complex and dependent on a number of variables and spatial characteristics. One "green prescription" to plant more trees may not apply in the case of street canyons. The following set of studies helps to break down some of the factors to be considered, such as surrounding structures, wind direction and wind speed.

In general, it appears trees can act as an effective barrier to traffic pollutants but at the same time may increase pollutant concentrations within the street canyon itself. Several studies challenge earlier studies that promote dense urban tree cover (Escobedo & Nowak 2009; McPherson, Simpson, Xiao, & Wu, 2011), at least in certain densely built street canyons, where a loss of ventilation may increase local exposure. A modelled study by Steffens, Wang and Zhang (2012) found that roadside particulate matter was reduced with the increase of leaf area density (LAD) and that increased wind reduces particle concentration larger than 50 nanometres but has a minimal effect on particles smaller than 50 nanometres (Steffens et al., 2012). However, Salmond et al. (2013) found that the presence of leaves on trees reduces the upward transport of vehicle emissions and increases air pollution within the canopy space and reduces the downward movement of fresher air from above. This suggests that the presence of leaves may increase storage of both NO and NO2 within the street canyon during periods when traffic emissions are high (Salmond et al., 2013).

Airflow is a critical component of tree-siting decisions in street canyons. Vos et al. (2013) found that trees and other types of vegetation can reduce the ventilation responsible for diluting traffic-emitted pollutants (Vos et al., 2013). This aerodynamic effect can be stronger than the pollutant-removal capacity of vegetation. Amorim, Rodrigues, Tavares, Valente and Borrego (2013) reported that trees can lead to the formation of pollution hot spots due to the rearrangement of airflow structures. CO concentrations were found to increase by an average of 12 per cent due to the action of trees blocking airflow and reducing ventilation. However, for parallel wind, a general decrease of 16 per cent on CO concentrations was observed due to enhanced ventilation and dispersion within the street canyon (Amorim et al., 2013).

Air quality can be additionally reduced due to building configurations that reduce wind speeds and air flow (Buccolieri et al., 2011). A modelling study by Wania, Bruse, Blond and Weber (2012) found that particle concentrations increase with both height-to-width ratios of streets flanked by buildings as well as the density of vegetation. Similarly, two studies by Buccolieri et al. (2009) found tree-planting led to a large increase in pollutant concentrations within the street canyon when compared to the tree-less case and suggest that a wider street canyon with two parallel rows of trees to maximize airflow is preferable to a narrow street canyon with only a single row of trees (Buccolieri et al., 2009; Buccolieri et al., 2011).

In summary, the confluence of traffic emissions, the trees' effect on air flow, local wind conditions and the three-dimensional configuration of the street and buildings need to be considered to determine the benefits of tree-planting in certain street canyons. In general, Vos et al. (2013) suggests that the filtering capacity of trees on the average urban roadside will be positive.

Mixed neighbourhood greenspace: Overview

This review defines mixed neighbourhood green space as the mix of overall neighbourhood-level green spaces that may include a combination of grass, trees or other vegetation. Studies in this category generally explore the impact of overall vegetation cover at the neighbourhood level. Neighbourhood-level green space cover and connectivity can significantly affect land surface temperature. However, there is little data on the impact of neighbourhood level green space on air temperature and thermal comfort. One study demonstrated inequitable distribution of heat burdens related to neighbourhood green space (Huang, Zhou & Cadenasso, 2011). However, there is very little data on neighbourhood-level green space and thermal discomfort or heat-related stress. The first known study to examine the relationship between neighbourhood green space and personal exposure to air pollution found a relationship at the household level, but more research is needed to understand how local green space affects individual air pollution exposure.

Mixed neighbourhood green space and heat

At the neighbourhood level, increased green space cover and high connectivity between neighbourhood-level green spaces are associated with cooler air temperatures and reduced urban heat island effects, particularly on hot days (Steeneveld et al., 2011).

Li, Zhou, Ouyang and Zheng (2012) and Li, Zhou and Ouyang (2013) found that the patch area of green space and configuration is significant to cooling. They found that the percentage cover of green space (PLAND) showed consistently negative correlation with land surface temperature across varying spatial resolutions and that more closely linked and continuous green spaces have stronger cool island effects than smaller patches of green space. Increased total patch edges can also increase energy flow and exchange between green space and the area around it, which can decrease land surface temperature (LST) (Li et al., 2012; Li et al., 2013; Zhou, Huang & Cadenasso, 2011). In general, the density and size of green space was more important than the configuration, but the two are highly interrelated. It should be noted that studies by Li et al. (2012) & (2013) found that the relationship between LST and configuration of green space might be scale-dependent, and therefore multi-scale and multi-region comparison studies on this relationship would be useful.

Increased neighbourhood-level green cover is also associated with reduced air temperatures. A comparison of green cover areas at a university campus in Japan found that greener campus areas were between 0.7 and 1.43°C cooler than non-green spaces and contributed to lower ambient air temperatures around campus (Srivanit & Hokao, 2013). Their findings may be underestimated because they did not account for shading from trees.

In terms of neighbourhood distribution of green space and heat, Huang et al. (2011) found that higher

LST was significantly associated with lower income neighbourhoods with larger proportions of ethnic minorities and older adults. The study shows inequitable distribution of heat exposure related to neighbourhood green space that is positively correlated with the distribution of disadvantaged populations (Huang et al., 2011). However, this study used LST data to represent UHI, which does not take the vertical surface temperatures variation and air volume temperature in the streets into account, which is important for understanding the actual experience of heat stress in neighbourhoods.

Mixed neighbourhood green space and air quality

Only two studies on air quality and neighbourhood green space were identified. The first study to examine the impact of neighbourhood greenness on personal exposure to air pollution found that greater residential greenness was associated with significantly lower personal exposure to PM2.5 at the household level (Dadvand et al. 2012). However, findings are limited by the fact that measures of indoor greenness were not evaluated. Levels of indoor greenness may have an effect on indoor air quality and confound the results. Also, because the vegetation index does not distinguish between the types of vegetation, exposure misclassification is possible.

Morani, Nowak, Hirabayashi & Calfapietra (2011) found that neighbourhood-level air quality depends on growth of the surviving tree population. Although tree populations can decrease in numbers, benefits can increase depending on the growth of the surviving tree population, and therefore proper tree siting in areas where they are best hosted can affect neighbourhood-level air quality (Morani et al., 2011).

Large urban parks: Overview

An urban park was categorized as "large" if it was reported to be over one hectare or was referred to as large. The cooling effects of large parks are influenced by a number of factors including time of day, configuration of the urban landscape and park configuration. It is suggested that closely spaced and/or connected smaller parks with trees can provide greater cooling to adjacent urban areas than single large parks with large open grass areas. Parks with larger trees may provide greater air-quality improvements.

Large urban parks and heat

Three studies reported significant cooling effects from large parks and one study did not. All four studies respond to the gap identified by Bowler et al. (2010) regarding the need to examine the ability of parks to provide cooling beyond its boundaries.

Studies by Doick et al. (2014) and Hamada & Ohta (2010) (both in warm temperate fully humid climates) report cooling effects from large parks. A 111-hectare park in London, England, generated an evening cooling effect from 20 metres to up 440 metres beyond park boundaries (Doick et al. 2014). In Nagoya, Japan, Hamada & Ohta (2010) also reported fluctuating cooling distance. During the night, the cooling effect of the green area from the edge of the site reached 200 to 300 metres into the urban area. During the day the cooling effect reached a maximum of 500 metres with wide fluctuations and a strong negative correlation between forest-cover ratio and air temperature in the late day/early evening hours (Hamada & Ohta, 2010).

In contrast, a study in the warm temperate dry summer climate (Cs) of Athens, Greece, reported that at the city scale, a national garden was cooler than the other monitored urban locations in the city, especially at night. However, at the micro-scale there was no clear cooling effect from the park on its immediate surrounding area. The authors found that the built urban form had a greater influence on daytime temperatures than proximity to the park. Streets with tall buildings and less sun exposure had lower air temperatures and streets with high heat sources (i.e., car emissions) were hotter (Zoulia et al., 2009). Hamada, Tanaka and Ohta (2013) also found that specific land-use types appeared to interfere with the extent of park cooling as well as the spatial distribution of the cooling effect. Commercial areas with more concrete and heat from traffic interrupted the flow of park cooling, while other types of urban areas expanded park cooling more effectively. However, in contrast to Zoulia et al., they found temperatures of all land-use types lowest near the park.

All studies found that temperature differences between parks and non-green sites were greatest during the hottest periods of the day and that trees contributed to greater cooling effects than large open spaces with grass (Hamada et al., 2013; Doick et al., 2014).

Doick et al. (2014) and Hamada & Ohta (2010) conclude that maximizing the connectivity of many scattered parks throughout the urban environment (rather than in one concentrated spot) will maximize cooling effects beyond park boundaries by breaking up the “micro” effects of the urban form that can cause hotter and cooler pockets.

Large urban parks and air quality

Few studies on the pollution mitigation impacts of large parks were identified. Among the pollutants investigated, the highest removal rates were found for PM10 and O3 (Cavanagh, Zawar-Reza & Wilson, 2009; Millward & Sabir, 2011; Paoletti, Bardelli, Giovannini & Pecchioli, 2011). Tree size and tree density were found to have an effect of pollution mitigation. Paoletti et al. (2011) reported that the removal of pollutants per tree increased over time as the tree grew in size. Cavanagh et al. (2009) found that higher densities of tree canopy were beneficial and reported a significant decrease in particulate PM10 concentration with increasing distance into the park forest.

Urban forests: Overview

The urban forest is the sum of all urban trees, shrubs, lawns and pervious soils in urban settings (Escobedo et al. 2011). The density and spatial configuration of the urban forest clearly affects land surface temperatures in the city. It is clear that urban forests are critical for improving urban air quality, but reliable air pollution mitigation estimates are difficult to determine using modelling scenarios. Balancing urban forest density, particularly in areas with low tree density, would greatly improve both local and city-wide urban air quality.

Urban forests and heat

All studies agree that urban forests mitigate urban heat island (Choi, Lee & Byun, 2012; Dobrovolny, 2013; Hart & Sailor, 2009; Kong, Yin, James, Hutyra & He, 2014; Li, Song, Cao, Zhu, Meng & Wu, 2011; McPherson et al., 2011; Rinner & Hussain, 2011). Most of the studies examine how land-cover patterns of green space at the city scale affect the urban heat island.

Comparing studies of the heat-mitigating effects of urban forests is challenging because each city is highly complex and unique, with different climates, urban configurations, building densities and green densities. Some studies account for these variables but not others. As a result, the evidence base is highly diverse. Despite this complexity, there is some important agreement among the findings regarding the need to improve green density as well as balance the distribution of various types of land-cover features to maximize urban cooling.

Significant negative correlations between land-surface temperatures and city-scale vegetation density have been documented across all climate settings included in this review (Dobrovolný, 2013; Kong et al., 2014; Li, et al., 2011). Overall vegetation density is found to have a significant impact on urban heat island. For example, field research in the warm temperate fully humid climate (Cf) of Nanjing, China, found that the spatial pattern of urban cooling was strongly correlated with spatial patterns of the urban forest where a 10 per cent increase in forest vegetation area resulted in a decrease of 0.83°C in surface temperature (Kong et al., 2014).

Remote sensing of land-surface temperatures in the warm temperate fully humid climate (Cf) of Shanghai, China, also found a strong negative linear relationship between land surface temperature (LST) and vegetation density over the region but an even stronger negative linear relationship between LST and vegetation fraction, the amount of vegetation cover in a given area (Li, et al., 2011). Similarly, in Toronto, Canada, remote sensing of land-surface temperature showed significant differences between the average temperatures of land-use types. Parks and green spaces were on average 4°C cooler than non-green areas, and higher concentrations of green space were associated with greater cooling (Rinner & Hussain 2011).

In general, the evidence suggests that vegetation cover can significantly reduce land-surface temperatures. Some limitations of these studies are worth noting. Remotely sensed measures of surface temperature do not represent human exposure to heat. Furthermore, recorded surface temperatures are constrained to the time of day the satellite crosses the study area, and therefore it is difficult to estimate how measures taken at different times of the day may affect findings. Also, in some cases only one daytime thermal image was used to compare variations in land-surface temperatures, which may not be representative of average trends (Rinner & Hussain, 2011).

Urban forests and air quality

Fourteen studies on the relationship between the urban forest and air quality were identified Thirteen reported air pollution reduction from urban forests (Alonso et al., 2011; Baro et al., 2014; Cabaraban, Kroll, Hirabayashi & Nowak, 2013; Escobedo & Nowak, 2009; Kroeger et al., 2014; Manes et al., 2012; McPherson et al., 2011; Nowak, Hirabayashi, Bodine & Greenfield, 2014; Nowak, Hirabayashi, Bodine & Hoehn, 2013; Tallis, Taylor, Sinnett & Freer-Smith, 2011; and Tiwary et al., 2009). Among the studies of green space and air pollution, economic benefits associated with air pollution mitigation appear most often in the literature on urban forests.

Urban forests are particularly important for reducing airborne particulate matter (Baro et al., 2014; Nowak et al., 2013; Tallis et al., 2011). Different capture rates have been documented at the city scale, and are most likely attributed to the varying structures of the cities and urban forests studied. Regional modelling estimates in England determined that the tree canopy of the urban forest in the Greater London Area removed between 852 and 2121 tonnes of PM10 annually, which equates to between 0.7 per cent and 1.4 per cent PM10 air-quality improvement. Regional plans to increase tree cover from the current 20 per cent to 30 per cent are expected to remove 1.1 to 2.6 per cent by the year 2050 (Tallis et al., 2011). In the United States, modelling of 10 cities found that the total amount of PM2.5 removed annually by trees varied from 4.7 tonnes in Syracuse to 64.5 tonnes in Atlanta (Nowak et al., 2013). However, certain assumptions may limit accuracy of the findings. For example, even though wind speeds vary locally, an average wind speed was used to represent the entire city (Nowak et al., 2013).

Urban forests also mitigate tropospheric ozone (Alonso et al., 2011; Baro et al., 2014; Kroeger et al., 2014; Manes et al., 2012). A study in the warm temperate dry summer climate (Cs) of Barcelona compared the removal capacity of various pollutants by the urban forest. It estimated the total annual O3 removal by Barcelona's urban forest at 305.6 tonnes. PM10 removal was the highest among the five air pollutants analyzed, with annual removal estimated at 166 tonnes. NO2 was 54.6 tonnes and ground-level O3 72.6 tonnes. It was lowest for CO (5.6 tonnes) and SO2 (NO NUMBER INDICATED). However, the accuracy of models is still limited due to the complexities and uncertainties in quantifying air pollution removal rates, including environmental thresholds (i.e., pollution levels that damage plant functions) (Baro et al., 2014).

In neighbouring Madrid, a modelled conversion of a large forested area to bare soil resulted in a significant increase in tropospheric O3 concentrations up to 15.6 per cent in the surrounding areas (Alonso et al, 2011). Another model in the warm temperate fully humid climate (Cf) of Texas estimated that a 405-hectare peri-urban forest could remove approximately 310 tonnes of O3 and 58 tonnes of NO2. However, the study did not account for forest growth or potential disturbances like drought, wildfire, pests and diseases, or hurricanes (Escobedo & Nowak, 2009; Kroeger, et al., 2014).

Estimates of air-pollution removal by the urban forest are mainly based on projected averages at the scale of the city (Escobedo & Nowak, 2009). Recognizing that urban forests are not uniformly distributed across a city, Escobedo and Nowak (2009) examined how differences in allocation of the urban forest in the warm temperate dry summer climate (Cs) of Santiago, Chile, influences air-pollution removal at the socioeconomic level. They found that low-income neighbourhoods had the highest PM concentrations in the city and a low tree density. It is suspected that lower tree cover is contributing to higher PM10 suspension rates in these neighbourhoods.

There is emerging evidence on the economic value of urban forests. The first known study to examine the air quality effects of all trees and forests in the conterminous United States showed 17.4 million tonnes of air pollution were removed in 2010, with human health effects valued at US$6.8 billion. The average annual percentage air-quality improvement due to trees varied among pollutants and ranged from a low of 0.13 per cent in urban areas for PM2.5 to a high of 0.51 per cent in rural areas for O3 (Nowak et al., 2014). However, due to a limited number of national weather and pollutant monitoring stations, national pollutant concentrations may be overestimated if using urban monitors to represent rural areas. Conversely, uncertainties associated with estimating tree cover, leaf area and boundary layers likely mean pollution reduction estimates are conservative. Lastly, economic values are only associated with air-quality improvements. Other positive impacts (e.g., heat mitigation) or trade-offs (VOC emissions) were not considered.

A modelling study estimated that increasing the Los Angeles urban forest by one million trees would lead to a reduction in PM10 (ranging from 1,674 tonnes to 2,618 tonnes or US$19 to $29 million USD), reduction in O3 (2,204 to 3,459 tonnes or $18 to $28 million), and a reduction in NO2 (1,768 to 2,757 tonnes or $15 to $23 million) over 35 years. The overall value of this benefit was estimated to range from $53 to $83 million over the 35 years based on high and low tree mortality scenarios, respectively. Interception of PM10 and uptake of O3 and NO2 were especially valuable. The dollar values associated with these benefits are calculated based on a combination of estimated reductions in electricity and natural gas consumption, atmospheric carbon dioxide reductions, air-quality improvements, reductions in storm-water runoff and aesthetic appeal. The study did not monetize possible health benefits associated with tree-planting (i.e., related to air pollution mitigation), so it is expected that these values are underestimated. The study also did not quantify the costs of site preparation, tree production and planting, maintenance and monitoring of trees (McPherson et al., 2011).

While it is clear that urban forests are critical for improving urban air quality, reliable estimates of air pollution mitigation are difficult to determine given the great number of variables considered in modelling scenarios. However, it is suggested that maximizing urban forest development, particularly in areas with low tree density and high levels of PM10, would greatly benefit urban air quality both within and across urban neighbourhoods (Tallis et al., 2011).

Comparisons of green space types and scales

Relatively few studies compare the impact of different green space types and scales on heat and air quality. In general, larger green spaces with a predominance of trees appear to be best for UHI mitigation, thermal comfort and improved air quality. However, the combined benefits of green roofs and walls for cooling and pollution mitigation make them an important alternative in high- density urban areas where ground space for greening is limited.

Comparisons and heat

Almost all of the studies comparing heat-mitigating effects of different scales and types of green space have been published in the last two years, responding to an important gap identified in previous reviews.

While all scales and types of green spaces studied showed cooling effects, green spaces with a predominance of mixed trees appear to have the greatest cooling ability in terms of urban heat island mitigation and providing thermal comfort and relief from heat stress (Chen, Yao, Sun, & Chen, 2014; Cohen, Ng, Chen, Wang & Yuan, 2012; Perini & Magliocco, 2014; Potcher & Matzarakis, 2012; Zhang, Lv, & Pan, 2013). For example, remote sensing to compare land surface temperatures of various green spaces in the warm temperate fully humid climate (Cf) of Beijing, China, found that treed green spaces provided the greatest cooling potential in summer over spaces with shrubs, grass or croplands (Chen et al., 2014). Similarly, in the warm temperate dry summer climate (Cs) of Tel Aviv, a comparison of the cooling effects of three urban parks, three street canyons, two urban squares and lawn spaces was conducted. All sites were a similar distance from the sea to control for local climate effects. The results showed that treed urban parks with a dense canopy provided the maximum cooling effect during summer, reducing temperatures by up to 3.8°C and thermal comfort values by up to 18°C PET (Physiological Equivalent Temperature) (Cohen et al., 2012).

A major comparison of green space scales was conducted in another warm temperate dry summer climate (Cs). The cooling effects of five different green roofs scales (ranging from 12,000 to 72,000 square metres) and five different ground vegetation scales (ranging from 30,000 to 37,900 square metres) were examined. Vegetation on the ground was made up of trees (with different heights and densities), two-metre-high hedges and grass. Green roofs were planted with grass. The study found that compared to non-vegetated sites, all vegetated sites reduced summer temperatures and improved thermal comfort. However, the green areas on the ground (grass, shrubs, trees) were more effective compared to green roofs in reducing mean radiant temperatures and thermal comfort at the street level. Temperature differences of around 3.5°C between a green area with grass and trees and a similar "no green" area were found. These findings are in line with a similar study in warm temperate dry winter climate (Cw) of Hong Kong where a modelled comparison of green roofs and ground-level vegetation (among 33 sites in total) found that while all green space types were beneficial in mitigating the urban heat island and providing thermal comfort, especially during the hot summer months, green spaces with trees provided the greatest cooling effects and were more beneficial than grass surfacing.

Ground-level greening was also found to be superior to rooftop greening given the large amount of tall buildings in Hong Kong (Ng et al., 2012). In general, it was found that green roofs do not affect pedestrian cooling (Ng et al., 2012; Chen 2009) but can mitigate UHI by reducing the surface temperature of otherwise artificial materials as well as decreasing the cooling load of buildings (Perini & Magliocco, 2014).

Comparisons and air quality

Few studies compared the effectiveness of different green space types on air pollution mitigation. There is some evidence that green walls in street canyons are more effective than green roofs for mitigating in-canyon air pollution and may perform better than trees in areas where wind flow is reduced (Amorim, Rodrigues, Tavares, Valente & Borrego, 2013; Buccolieri et al., 2011; Koyama et al., 2013). One study estimated that street-level reductions of as much as 40 per cent for NO2 and 60 per cent for PM10 are achievable using green walls and suggests that the potential benefits of green infrastructure for air quality have been substantially undervalued (Pugh, MacKenzie, Whyatt & Hewitt, 2012).

VEGETATION TYPES THAT INFLUENCE HEAT AND AIR QUALITY

Vegetation types and heat mitigation

Information on the performance of specific plants for green buildings is limited. In terms of living walls, Cameron, Taylor and Emmett (2014) found that plant species varied in their cooling capacity as well their mechanisms for cooling. Hedera and the silver-leaved, semi-herbaceous stachys performed the best for wall cooling. Prunus also provided significant air-temperature cooling but was less effective in its surface-temperature cooling when compared to stachys and hedera. When evaluated on a per leaf area basis, however, other species demonstrated greater cooling potential with fuchsia, jasminum and lonicera out-performing others. Fuchsia promoted evapotranspirative cooling, whereas shade cooling was more important in jasminum and lonicera. In terms of rooftop vegetation performance, Coutts et al. (2013) found that the use of sedum (a dry land plant species) provided no significant benefit over a soil substrate roof alone.

In terms of providing thermal comfort in a hot, humid park setting, compact multilayered plants are suggested over large grassy areas for cooling (Cao et al, 2010). When comparing trees and grass, grass surface composition is shown to have little effect on globe temperatures whereas tree shading was found to reduce globe temperatures by 5 to 7°C and reported to provide the greatest reduction of heat stress from their shade (Froehlich & Matzarakis, 2013; Armson et al., 2012). This suggests that while both grass and trees may help to reduce urban heat island, trees are more effective in providing relief to urban residents from heat stress. Where possible, trees are suggested over shrubs and grass for cooling as correlation analysis shows stronger correlation coefficients between their pattern metrics and urban cool islands, especially in warm seasons (Chen et al., 2014; Zhang et al., 2013).

In terms of tree types, deciduous trees have been identified as most important for providing thermal comfort in parks since they provide shade in hot months but do not block needed warmth from the sun in cold months (Lin et al., 2010, Hwang, et al., 2011). During summer, both deciduous and evergreen trees provided similar cooling effects, but in winter the evergreen tree park was much cooler and below the "neutral" comfort conditions (Cohen et al., 2012; Zhang et al., 2013). One study found that species with a lower canopy temperature like P. nigra, or tilia cordata are especially suitable for reducing local air temperatures; however, some species such as Q. robur and several species of populus as well as P. acerifolia should be avoided due to their high emissions of biogenic volatile organic compounds (BVOC) and potential contribution to ground-level ozone formation (Meier & Scherer, 2012). A comparison of small trees that grow in warm temperate climates with dry winters found that eucalyptus sp. had a significantly higher cooling effect, followed by olea. The species with the least effect on temperature were grevillea and cupressus (Feyisa et al, 2014). Comparisons of the cooling effects of specific tree species native to Canada were not found.

Only one study was identified that specifically compared the urban heat island mitigation effects of different plant compositions of the urban forest. A study of the urban forest of Beijing, China (Cf), showed that a combination of trees, grass and shrubs had the highest heat-absorbing capacity in the summer, followed by tree-grass and tree-only combinations. However, results should be considered very cautiously since there are no comparative studies and the current study did not consider confounders such as meteorological conditions, species composition, plant age and surrounding building environment (Zhang et al., 2014).

Vegetation types and air quality

Individual plant species exhibit vast differences in their ability to uptake pollutants (Rowe, 2011). A review on green roofs by Rowe (2011) reported that trees and shrubs were more effective in removing contaminants than herbaceous perennials due to greater leaf surface area; however, the added load requirements and costs of treed roofs limits the feasibility of this option (Rowe, 2011). The review also reported that air-quality improvements from green roofs could be maximized through plant selection. For example, the tobacco plant was found to have 30 times more N02 uptake capacity than commonly used sedum-like succulents. More recently, a comparison of four green roof species found that creeping bentgrass and red fescue had higher particle capture of PM10 than ribwort plantain and the more extensively used green roof species sedum (Speak et al., 2012). However, a study comparing the PM capture of common roadside plants in Berlin, Germany, found the overall amount of PM on the leaves of roadside species differed according to traffic density, particle type and species and found that the mitigation of a broader range of particles can be achieved by maximizing both the structural and species diversity of plants (Weber et al., 2014).

In terms of aesthetics, a combination of trees and shrubs is found in most urban parks. One of the first in-depth comparisons of eight different tree and shrub species found that they differed significantly in their ability to capture particulate matter. All plant species tested captured particulate matter of large (10 to 100 μm), coarse (2.5 to 10 μm) and fine (0.2 to 2.5 μm) fraction sizes, but spiraea japonica was the most effective while platanus × hispanica was the least effective with a more than twofold difference between the two (Dzierżanowski, Popek, Gawrońska, Sæbø & Gawroński, 2011). The work by Yin et al. (2011) suggests that in the highly urbanized Pudong District of Shanghai, an urban park patch of 10,000 square metres planted with a combination of 600 medium-sized trees and 10,000 low shrubs could reduce traffic-based air pollution by 30 per cent for PM10, 15 per cent for SO2 and 10 per cent for NO2 (Yin et al., 2011) from roadside to 100 metres of the park. However, the study only focused on ground-level pollutant concentration, which may result in an overestimation of removal rates (Yin et al., 2011).

The evidence is clear that trees are essential for mitigating air pollution; however, most of the evidence explores the impacts of overall abundance and distribution of trees and far less is known about the effects of specific tree types and species on air quality (Escobedo & Nowak, 2009; Manes et al., 2012). Ground-level data collected from 47 different woody plant species in Norway and Poland found that differences in particulate matter accumulation result from complex interactions between plant properties, climate and other environmental factors. For example, species pinus mugo and pinus sylvestris, taxus media and taxus baccata, stephanandra incisa and betula pendula were more efficient in capturing PM than other species such as acer platanoides, prunus avium and tilia cordata (Sæbø, Popek, Nawrot, Hanslin, Gawronska & Gawronski, 2012). Among the studies identified in this review, coniferous trees are found to be the best for capturing PM over evergreen broadleaf and deciduous species (Tallis et al., 2011; Tiwary et al., 2009). However, evergreen broadleaf and deciduous tree species have been found to remove more atmospheric O3 than conifer forests (Alonso et al., 2011).

In terms of BVOC emission, studies in a temperate, dry summer climate found that pinus pinea, aesculus hippocastanum and populus alba were the most effective species in removing CO, O3, NO2 and SO2 from the air, while A. hippocastanum was the most effective as filter for PM10. However, P. alba was a strong emitter of isoprene (a BVOC). The species that showed a high potential of ozone formation were P. pinea, A. hippocastanum, Q. robur, G. biloba, Q. ilex and mainly P. alba, while fraxinus ornus and carpinus betulus showed the lowest emission of total BVOCs (Paoletti, et al., 2011).

Despite the unique differences among tree species, a diversity of tree species can provide the most stable improvements in air quality. A study of evergreen broadleaf, conifer and deciduous species by Manes et al. (2012) found complementary air-pollution uptake patterns (related to tree physiology and phenology) across the seasons. For example, in spring, deciduous broadleaves showed the highest and conifers showed the lowest potential O3 uptake. In summer deciduous broadleaves showed a reduced O3 uptake while evergreen broadleaves were able to maintain high levels of potential O3 uptake and conifers showed increased O3 uptake. In fall, it changed again with higher values estimated for deciduous broadleaves and lower values for evergreen broadleaves and conifers. Their results suggest that increased diversity of tree species could provide maximum overall air-quality improvements and resiliency to seasonal and climatic fluctuations. Manes et al. (2012) also compared the BVOC emissions of these trees and reported that evergreen broadleaves include both strong and medium monoterpene emitters (like quercus ilex and Q. suber, respectively), deciduous broadleaves include both species with negligible VOC emissions (Q. cerris) and medium isoprene emitters (platanus x acerifolia, robinia pseudoacacia), while conifers are dominated by the medium monoterpene emitter pinus pinea (Manes et al., 2012).

VEGETATION CHARACTERISTICS THAT INFLUENCE HEAT AND AIR QUALITY

Vegetation characteristics and heat

The cooling capacity of green space is affected by many characteristics, including density, size, shape and spacing.

Density. Green space density is described in many different ways by different studies. For example, some studies examine density in terms of tree canopy cover (Feyisa et al., 2014); others refer to the relative percentage of vegetation in a given urban area (Ng et al., 2012). In general, many studies report a strong and significant association between various measures of increased green space density and increased cooling effects (Dobrovolný, 2013; Feyisa et al., 2014; Hart & Sailor, 2009; Ng et al., 2012; Perini & Magliocco, 2014; Vidrih & Medved, 2013; Weber et al., 2014; Zhang et al., 2013). In particular, tree density is important. For example, a very significant negative relationship was observed between temperature and canopy cover where the temperature dropped by 0.02°C for every percentage increase in tree canopy cover (Feyisa et al., 2014).

The amount of tree-planting needed to lower pedestrian-level air temperature by around 1°C is estimated at 33 per cent of the total urban area (at least one-third of total land area) (Ng et al., 2012). Other studies found that cool islands are created when forest vegetation occupies over 61.2 per cent of a 240-square-metre area (Kong et al., 2014) and when tree shade on a street is increased from eight per cent to 50 per cent (leading to an estimated mean radian temperature decrease of 13.6 K and to a PET decrease about 8.3 K at the hottest periods of the day in summer) (Shashua-Bar et al., 2012). A study by Vidrih and Medved (2013) reported that a park of 130 metres with planting density of 45 trees per hectare, with an age of 50 years, could provide air temperature cooling up to −4.8°C (optimal soil water conditions for maximal evapotranspiration of trees and grass was assumed) (Vidrih & Medved, 2013). In terms of urban heat island mitigation, the amount of vegetation cover may be more important in determining urban land surface temperature than the degree of urbanization (represented by density of buildings) (Dobrovolný, 2013; Hart & Sailor, 2009; Weber, et al., 2014).

Size. A strong and significant association has been reported between green space size and increased cooling effects (Cao et al., 2010; Chen et al., 2014; Dobrovolný, 2013; Feyisa et al., 2014; Hart & Sailor, 2009; Li et al., 2012; Onishi et al., 2010; Susca et al., 2011; Weber et al., 2014;). For example, modelling showed that an urban cooling island (UCI) was found to increase with the length of the park and larger green space sizes were significantly associated with UCIs, either because less heat from built-up areas is emitted to the centre of the green space, or because more of the cool air is built up and sent out from the centre (Vidrih & Medved 2013). While the size of the green space was found to affect UCIs in all seasons, it appears to be especially strong in summer (Chen et al., 2014, Li et al., 2012; Onishi et al., 2010; Susca et al., 2011). While cooling effects have been documented in small parks, land surface temperature analysis of 92 parks by Cao et al. (2010) showed that larger parks have stronger cooling effects and that UCIs only exist when parks are larger than a certain threshold (two hectares in the study). However, it is important to note that this threshold is for reduction of surrounding surface temperature and parks under two hectares can still provide thermal comfort via shade (Cao et al., 2010).

Shape and spatial configuration. Urban heat mitigation may be achieved by increasing the relative amounts of green space, but also by optimizing the spatial configuration of green space (Choi et al., 2012; Rinner & Hussain, 2011). For example, there is some evidence that small parks spaced closely together could improve overall heat health of urban areas. Feyisa et al. (2014) found that a cooling effect of 3.93°C (ranging from 0.11 to 6.72°C) was found from the edge of each park to a maximum cooling distance of 224 metres (Feyisa et al., 2014). This park cooling distance (PCD) was significantly and positively related to the size and shape of the park. In Seoul, Korea (snow climate with dry winter — Dw), remotely sensed data showed that cooling effects from urban green areas can extend to around four kilometres and that the ratio of urban heat area to urban cooling area increases with distance from a green space boundary. The authors therefore suggest a maximum distance of four kilometres between green spaces would reduce urban heat island effects (Choi et al., 2012). Similarly, in the warm temperate fully humid climate (Cf) of Shanghai, a strong significant correlation was found between mean land surface temperatures and landscape metrics. They found that residential land areas with low- to middle-rise buildings and low vegetation cover had significantly higher temperatures than areas with denser highrise buildings with high vegetation cover (Li et al., 2012). This suggests that while building density contributes greatly to surface urban heat islands, cool islands can be provided through consistently spaced green areas in high urban density areas.

Vegetation characteristics and air pollution

Vegetation density. Vegetation density is the predominant green space characteristic associated with increased pollution mitigation from urban forests (Yin et al., 2011; Dzierżanowski et al., 2011; Escobedo & Nowak, 2009; Nowak et al., 2014,Nowak et al., 2013; Tallis et al., 2011; Tiwary et al., 2009; Tsiros, Dimopoulos, Chronopoulos & Chronopoulos, 2009). For air pollution studies green space density is generally described in terms of relative tree cover (i.e., crown cover, leaf area density and leaf area index). Tree size and density effect pollution mitigation rates. For example increased tree cover is positively associated with increased mitigation of PM, O3, NO2 and SO2 (Escobedo and Nowak, 2009, Nowak et al., 2014; Nowak et al., 2013). Paoletti et al. (2011) reported that the pollutant removal rates of trees increased over time as the tree grew in size. Cavanagh et al. (2009) found that denser tree canopies were associated with greater air quality. Yin et al. (2011) reported that crown volume coverage (CVC) of trees was positively associated with pollution removal rates (PM10, SO2 and NO2) and the study suggests that a CVC value of 2.0 m3/m2 was a good target threshold for park design. Tallis et al. (2011) report that increased tree cover in London, England, from the current 20 per cent to 30 per cent will result in an increased annual PM capture of 18 per cent above 2006 levels. While larger trees with greater canopies are generally capable of removing more PM10, Tiwary et al. (2009) report that younger, smaller trees are still effective in removing PM10 due to their greater foliage densities.

Plant height. There is some evidence that compact trees and shrubs growing low to the ground (such as *Spiraea japonica*) are more effective for PM capture than large, branchy trees (such as *P. hispanica*) (Saebo et al., 2012; Dzieranowski et al., 2011).

Plant leaf characteristics. Emerging evidence shows the importance of plant leaf traits on PM mitigation. Increased PM capture is associated with greater plant hair density (Speak et al., 2012), plant leaf density (Speak et al., 2012), greater leaf wax (such as species like B. pendula), and broader leaf surfaces (Hwang et al., 2011; Dzierżanowski et al., 2011). Leaf surface roughness was not found to be significant to PM accumulation in a study by Saebo et al. (2012). They found that pine species were particularly efficient at capturing PM despite the lack of leaf hair or rough surface. Studies by Tiwary et al. (2009) and Tallis et al. (2011) also found pine foliage to rank the highest in terms of PM accumulation.

MODIFYING VARIABLES: FACTORS THAT AFFECT THE INFLUENCE OF GREEN SPACE ON HEAT AND AIR QUALITY

Understanding modifying variables is highly complex because they do not act in isolation but create complex scenarios that affect heat and air quality in a real-world setting. For example, both air temperature and relative humidity are influenced by wind speed and direction. High wind speeds result in a large volume of cool energy, which can maximize air pollution mitigation (Srivanit & Hokao, 2013). This section on modifying variables merely identifies some of the modifiers that influence the relationship between green space, heat and air pollution. For an in-depth investigation of the confluence of these variables see Baik et al. (2012); Doick et al. (2014) and Tsiros et al. (2009).

Modifying variables: Green space and heat

Many variables, such as wind, temperature/season, the surrounding built environment and precipitation, can modify the cooling influence of green space.

Wind. Trees can decrease wind speeds on streets, leading to increasing temperatures inside street canyons. However, the benefit of thermal comfort provided by tree shade is thought to outweigh the possible loss of wind speed from trees (Lin et al., 2010; Park et al., 2012; Shashua-Bar et al., 2012). Wind generally increases the cooling effect of parks (Doick et al., 2014; Oliveira et al., 2011). During light wind conditions, warm air in the streets rises, drawing cool air from the park into the streets, causing cooling. At higher wind speeds, these currents and the associated cooling effect of the park are disrupted (Doick et al., 2014; Zoulia et al., 2009). However, some evidence suggests the density and age of trees have a greater effect on cool islands provided by urban parks than wind (Vidrih & Medved, 2013)

Temperature and season. The cooling effects of green space are significantly greater during the hottest temperature months and the hottest periods of the day when relief from heat is most needed (Bowler et al., 2010; Cao et al., 2010; Cohen et al., 2012; Hamada et al., 2014; Hwang et al., 2011; Meier & Scherer, 2012; Lin et al., 2012; Oliveira et al., 2011; Park et al., 2012; Sung, 2013; and Zhang et al., 2013). Increased temperature was also found to increase the cooling capacity of green walls (Hamada & Ohta, 2010; Koyama et al., 2013). UHI mitigating effects from urban forests were stronger in summer than in spring (Li et al., 2012). This is assumed to be a result of increased foliage in summer as opposed to spring, which also emphasizes the importance of dense foliage for urban cooling.

Built environment. Many aspects of the built environment, such as building density, heights and arrangement, can significantly influence airflow, and thereby the cooling range of green spaces into surrounding urban areas (Li et al., 2012, Li et al., 2013; Zoulia et al., 2009). During the summer the highest temperature values are often found in east-west-oriented street canyons because north-south-oriented street canyons are more shaded throughout the day (Cohen et al., 2012). Increased building height and density are strongly correlated with increased land-surface temperatures, which may reduce the cooling effects of the urban forest (Weber et al., 2014). In terms of site orientation, trees along roads or surrounded by impervious surfaces are relatively warmer than park trees; therefore, it is suggested that siting trees to follow the sun to create maximum combined shading from trees and buildings is important to maximize cooling (Lin et al, 2012).

Irrigation. Precipitation and/or irrigation is necessary for green roofs to provide any substantial microclimate benefit during the day (Coutts et al., 2013; Zinzi & Agnoli, 2012), which may be a challenge since cooling and alleviation from heat stress are most needed under dry conditions. Therefore, relying on rainfall, particularly in dry climates, may limit the cooling capacity of green roofs. The cooling effect of plants on air temperatures may be severely limited if ideal water and soil conditions that support evapotranspiration are not met (Vidrih & Medved, 2013).

Modifying variables: Green space and air pollution

Plant location, pollution levels, wind, season/temperature and precipitation can all modify the air-pollution mitigating effects of green space.

Plant location. The degree to which plant location affects levels of air pollution mitigation is unclear.

Findings generally point to the combined effect of other modifiers such as wind, microclimate and local pollution levels (Saebo et al., 2012; Tallis et al., 2011). For example, Tallis et al. suggest that the deposition of pollutants on plants depends on factors such as the pollution concentration and climatic factors where the plant is located (Tallis et al., 2011). However, Saebo et al. 2012 measured particulate matter accumulation on the leaves of 22 trees and 25 shrubs at multiple test fields in Norway and Poland over two years. They found that plant species (and not location) were a better predictor of PM accumulation on plants. Species found to accumulate a relatively high amount of PM (such as B. pendula) did so despite different locations and environments. Conversely, species accumulating little PM (such as A. platanoides and A. pseudoplatanus) set in locations with relatively high levels of air pollution were also the less efficient in locations with low levels of air pollution. The authors suggest PM accumulation by plants generally depends more on species-specific properties than plant location.

Pollution levels. As mentioned above**,** there is debate over whether or not the closer proximity of plants to air pollution results in greater exposure, capture and uptake of air pollutants. For example, while some studies report increased particulate matter removal by plants in areas with more air pollution (Tallis et al., 2011), other studies report that the plant species (and not pollution levels) are a greater predictor of PM removal rates (Saebo et al., 2012). Also, in some cases, if pollution levels are too high, plants can be damaged or destroyed (Manes et al, 2012; Morani et al., 2011; Roy et al., 2012).

Wind. Improvements in air quality tend to occur under windy conditions (Alonso et al., 2011; Nowak et al., 2013; Srivanit & Hokao, 2013). However, the impact of wind on the pollution mitigating effects of green space is highly complex, particularly in the context of urban streets. Pollutant concentrations in an urban street canyon depend on the amount of wind present to carry pollutants away. For example, a study in Lisbon on the dispersion of traffic-based carbon monoxide (CO) emissions at the pedestrian level found that for an incoming wind direction of approximately 45° on one street, CO concentrations increased by approximately 12 per cent due to the effect of trees on the exchange rates with the air above roof levels. However, a street with parallel winds showed a CO concentration decrease of about 16 per cent due to better ventilation (Amorim et al., 2013). In the case of green roofs, site-specific winds also affected street canyon air quality. PM mitigation effects were significant with a roof located downwind of a major emission source but not significant for a green roof with prevailing winds that crossed the roadway before reaching the roof (Baik et al., 2012; Speak et al., 2012). In cases of low wind speeds, green walls may offer considerable potential for reductions in street canyon air pollution and may act as a buffer against pollution hot spots (identified by Amorim et al., 2013).

Season/temperature. Average values for seasonal removal of air pollution show a similar pattern across pollutants where uptake was lowest for all pollutants in winter and highest in the spring and summer (Baro et al., 2014). Ozone deposition rates may be higher in spring than in summer, showing that drought stress may lower the sink activity for O3 pollution (Alonso et al., 2011; Escobedo & Nowak, 2009).

Precipitation. Increased precipitation also tends to increase the ability of urban forests to remove PM because it washes particles from the leaf surfaces. Lower removal rates were found in areas with lower precipitation (Nowak et al., 2013). Stomatal conductance of deciduous trees appears to be more affected by drought conditions, and coniferous trees were found to be more drought-tolerant (Manes et al. 2012).

Negative impacts associated with green space

Two main negative impacts were identified in the literature. The first is that increased green density from trees or other plants may increase street canyon air pollution leading to much higher exposure for pedestrians in the canyon, which could be detrimental to health, particularly in populated areas (Amorim et al., 2013; Morani et al., 2011). While street trees were found to reduce street-level PM10 they increased NO2 concentrations in highly polluted canyons in most circumstances (Pugh et al., 2012). However, for streets with moderate or low emissions, trees showed an "unambiguously beneficial effect"(Pugh et al., 2012).

The other possible negative impact of green space relates to evidence that some trees emit biogenic volatile organic compounds. BVOC emissions can increase levels of ground-level ozone when mixed with NO2 (e.g., from traffic) in the presence of sunlight (Escobedo & Nowak, 2009; Roy et al., 2012). Higher BVOC measures are generally found in vegetated urban areas (Bao et al., 2010; Baro et al., 2014; Roy et al., 2012) and have been found to contribute to increased ground-level ozone (Bao et al., 2010). However, green spaces such as forests can also act as sinks for ground-level ozone, even among forests with high BVOC-emitting tree species. A study in Madrid found removing a large urban forest led to increased ground-level ozone both within and downwind of the modified area (Alonso et al., 2011). Alonso et al. (2011) note that their results support the conclusion by Nowak et al. (2000) that the capacity for urban forests to remove ground-level ozone is greater than the potential ozone production resulting from BVOC chemical interactions.

Trade-offs associated with green space

The cost of green space in relation to benefits was the main trade-off explored in the literature. Similar to the finding by Roy et al. (2012), this review found little cost-benefit analysis related to siting, planting and maintaining urban green spaces, which is assumed to be significant. However, a lack of findings may be due to limits of the search strategy.

One modelling study estimated that the cooling effects from a program to plant a million trees throughout Los Angles would decrease air-conditioning energy consumption by 917 GWh per year but that this cooling savings would be partially offset by increased heating costs from tree shade that obstructs winter sunlight. Tree shade was expected to increase natural gas required for heating by 134,206 GJ on average, valued at $851,000 (McPherson et al., 2011). It is likely to cost more to install and maintain a green roof than a simple high albedo roof.

Given the debate over the marginal cooling effect of green roofs compared to less expensive alternatives, the costs of green roofs for heat mitigation alone may be may be prohibitive (Mackey, Lee & Smith, 2012). However, this review did not identify studies that examined the combined benefits of thermal comfort, urban heat island mitigation and pollution mitigation from green roofs. Additional benefits of green roofs include reduced stormwater runoff and a number of other ecosystem services (Mackay et al., 2012). These benefits would be important for a comprehensive cost-benefit analysis of green roofs (Coutts et al., 2013; Smith & Roebber, 2011; Zinzi & Agnoli, 2012).

Direct health effects

Previous systematic reviews did not identify any studies that investigated the direct health effects of heat and pollution mitigation from urban greening (Bowler et al., *2010*). While there is a large and growing evidence base on the impacts of heat and air pollution on human health, as well as separate studies on heat and air pollution mitigation from green space, few studies directly associate observed pollution or heat mitigation from green space with direct health impacts (Nowak et al., *2014*). Over the past five years evidence on direct health effects is emerging.

At a local scale, Tiwary et al. (2009) observed that PM mitigation from trees was directly associated with reduced hospital admissions and death. They estimated that a 10-by-10-kilometre grid in London with a 25 per cent tree cover could remove 90.4 tonnes of PM 10, which they estimated prevented two deaths and two hospital admissions in that area per year. However, these benefits are only associated with PM reduction and it is expected the estimated direct health benefits would be much greater if calculations included mitigation of other pollutants. For example, NO2 reduction associated with trees in Portland was estimated to result in an annual US$7 million benefit as a result of decreased respiratory problems (Rao et al., 2014). The authors measured levels of NO2 at 144 sites in Portland, Oregon. After controlling for roads, railroads and elevation, they estimated that every 10 hectares (20 per cent) of tree canopy within 400 metres of a site was associated with a 0.57 ppb decrease in NO2.

In Rome, Italy, Alonso et al. (2011) estimated the three per cent decrease in O3 from a forested park corresponds to an estimated decrease of roughly three deaths a year, saving US$3 million (using a conservative estimate of the value of a statistical life from Blomquist, 2004). Conversely, increased O3 levels from removing the large forest in Italy were estimated to result in an increase of premature mortality risk by up to 0.9 per cent (Alonso et al., 2011). A similar climate study by Manes et al. (2012) valued the urban forest in Madrid at an estimated US$3 million a year based on mortality costs associated with O3 alone. For both studies the estimates are considered conservative since they do not consider impacts to morbidity and other health effects.

At city and regional scales, a study by Nowak et al. (2013) compared the health benefits of observed PM mitigation from trees for 10 U.S. cities. To estimate the effects and monetary values of PM2.5 removal by urban trees in all cities, the study estimated: 1) the total leaf area in each city on a daily basis, 2) the hourly flux and resuspension of PM2.5 to and from the leaves, 3) the effects of hourly PM2.5 removal by trees on PM2.5 concentration in the atmosphere, and 4) the health incidence impacts and monetary value of the change in PM2.5 concentration using information from the U.S. Environmental Protection Agency's Environmental Benefits Mapping and Analysis Program (BenMAP) model (see Nowak et al., 2013, for full range of input data). They found that PM mitigation from trees was directly linked to reduced mortality, hospital admissions and respiratory symptoms. The average health benefits value per hectare of tree cover was estimated at US$1,600. The health benefits from annual rates of PM mitigation varied from $122 million in Syracuse to $6.2 billion in New York, with an overall average of $1.6 billion. Overall, the greatest effect of trees on reducing health impacts of PM2.5 occurred in New York City due to a combination of a relatively high population density and high pollution-removal rates. In New York, PM2.5 removal was valued at US$60.1 million a year, attributed to reduced human mortality (Nowak et al., 2013).

At a national level, a first-of-its-kind study by Nowak et al. (2014) reported that a one per cent improvement in air quality from trees was associated with the avoidance of more than 850 deaths and 670,000 incidences of acute respiratory symptoms in the United States. The U.S. EPA's BenMAP program was used to estimate the incidence of adverse health effects (i.e., mortality and morbidity) and associated monetary value resulting from changes in NO2, O3, PM2.5 and SO2 concentrations due to pollution removal by trees (see Nowak et al., 2014, for full range of input data). These human health effects were valued at US$6.8 billion, mainly associated with reduced deaths. The greatest economic values associated with reduced adverse health effects from pollution removal are concentrated in urban areas, where population density is higher, with 68.1 per cent of the $6.8 billion value occurring in urban areas. This means that in terms of impacts on human health, urban trees are critically important. Because the study used BenMAP values and U.S. EPA air primary quality standards[3] for its estimates, the evaluations are considered conservative as they only address human health values related to four of the six criteria pollutants (Nowak et al., 2014).

No studies on heat-related mortality or morbidity associated with green space interventions were identified. The majority of heat-focused studies in this review examined surface temperature mitigation. Studies on changes in surface temperatures from green space are important for understanding urban heat islands but are not a good indicator for how green space can improve human thermal comfort and reduce human heat stress. For example, Lynn et al. (2009) showed that increased heat-reflecting surfaces (increasing surface albedo) to combat urban heat island in New York City may be detrimental to human health due to increased thermal stress at the street level from reflected solar radiation and emitted thermal radiation. They show that trees are better for reducing the energy load on a person by blocking downward solar radiation and thereby reducing the amount of reflected shortwave radiation from the surface.

Studies on thermal comfort provided by green space appear to have increased since the publication of the Bowler et al. (2010) review; however, no direct health impacts are documented. For example, a cross-sectional study of 800 people reported that longer and frequent visits to small urban parks are significantly associated with improvements to perceived well-being and relief from thermal discomfort during periods of heat stress (Lafortezza et al., 2009). The impacts of greening to protect against heat stress and related illness may be significant in light of Canadian findings showing that, on average, for every one-degree C increase in maximum temperature ambulance response calls for heat-related illness increased by 29 per cent (Bassil, 2010). Several studies also documented heat and air-pollution-related health inequalities associated with unequal distribution of trees and green space in urban areas (Escobedo & Nowak, 2009; Huang et al., 2011; Jesdale, Morello-Frosch & Cushing, 2013; and Su et al., 2011). The prevalence of these health inequalities and underlying inequities are in need of further investigation when considering emerging evidence in Canada that low-income, inner-city neighbourhoods with high populations are generally more vulnerable to heat-related health risks (Bassil et al., 2009).

3 For the U.S. EPA, "primary standards are designed to provide public health protection, while secondary standards provide public welfare protection, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings." (Nowak et al., 2014)

SUMMARY OF FINDINGS

All types of green space, from single green walls to large urban forests, have been associated with relief from heat stress, reduced urban heat islands and air pollution reductions. Green roofs and walls may not be as effective at cooling or reducing air pollution as ground-level trees but can provide important heat island and pollution mitigation services, particularly in densely built areas.

Both small and large parks can provide cool islands in cities. Spatial configuration may be more important than size when it comes to cooling. Parks that are connected and closely spaced can improve the flow of cool air through the city and thereby contribute to both cooling and air pollution mitigation.

Trees in the city are particularly crucial for reducing heat stress, reducing urban heat island and reducing air pollution. While other structures can provide shade, trees have the unique ability to provide micro-cooling through evapotranspiration and relief from heat stress through shade. However, caution is suggested when planting trees in urban street canyons. Factors such as wind direction, street orientation and building heights may result in increased in-canyon pollution due to tree-planting. Therefore, the benefits of tree-planting in street canyons are site-specific and should be considered on a case-by-case basis. Studies of BVOC-emitting tree species can also help in choosing low-emitting trees, particularly in high-traffic areas.

Some data indicate that increased neighbourhood green space is associated with lower surface and air temperatures as well as possible reduced exposures to air pollution at the household level. Several studies show inequitable distributions of neighbourhood green space that is often related to socioeconomic status. This may represent health inequities and inequalities related to heat and pollution burdens.

All studies of the urban forest report considerable cooling and pollution mitigation effects. Similar to parks, a greater amount of trees, green density and spatial connectivity increases the cooling and pollution-mitigating capacity of urban forests. Achieving the 30 to 50 per cent green density targets recommended by many study authors may require support for a diversity of green space types, including green walls and roofs and connected green path corridors..

Plant species vary in both their cooling capacity and cooling mechanisms. For example, some wall-covering plants perform better for air-cooling (e.g., prunus) while others are better at reducing surface temperatures (e.g., stachys or hedera). Research suggests that the wide use of sedum on rooftops provides no better cooling than soil alone. Other species such as creeping bentgrass, red fescue and tobacco plants are better for reducing air pollution.

In a park and urban forest setting, compact multi-layering of diverse species, particularly in humid climates, may be most beneficial for both cooling and air-pollution mitigation. Although deciduous trees provide an ideal balance of shade in summer while allowing the penetration of sunlight in winter, a diversity of tree species (including evergreen broad leaf and conifers) provides complementary air-pollution mitigating functions in four-season climates. Diversity also helps to improve the overall resiliency of the urban forest.

Although multiple possible confounding variables affect the cooling capacity of green spaces (such as building density), many studies report strong and significant associations between increased green space cooling and increased density, size and shape complexity of the green space. In terms of pollution mitigation, green space density appears to be the main characteristic of increased air quality in urban areas. Increased density can be represented by a number of factors, including the amount, size and leaf density of plants in a given area.

Wind may be one of the most important modifying variables for both heat and pollution mitigation. Wind generally increases the cooling and pollution-mitigating effects of green space. However, vegetation can also slow winds in street canyons, contributing to higher in-canyon pollution concentration. The confluence of building factors such as building heights and orientation with prevailing winds may affect cooling and air-quality improvements from green space.
Careful consideration of BVOC-emitting trees species and the configuration of street canyons will help to increase benefits and minimize negative impacts of urban greening in high-traffic areas.

Emerging evidence shows that pollution mitigation from urban green space can provide considerable direct health benefits, mainly in terms of reduced mortality. However, epidemiological evidence of the relationship between green space and heat-related health burdens is severely lacking.

An increase in Canadian-based research, as well as investigation into the micro-spatial distribution of green space within cities and how it relates to differential health burdens, is important to increase understanding of the relationship between green space and health.

RECOMMENDATIONS

Among the studies reviewed, some policy-relevant recommendations for urban greening were identified and are summarized below.

1. EXAMINE SPATIAL DIFFERENCES AT LOCAL SCALES AS PART OF LARGER GREENING STRATEGIES.

Greening strategies to mitigate urban heat and air pollution should apply a multi-scale approach across local communities, cities, regions and provinces (Baro et al., 2014). Although an urban forest may reduce heat and improve air quality, disparities in distribution can lead to "green deserts" and pollution "hot spots" at micro scales (Escobedo & Nowak, 2009; Huang et al., 2011; Jesdale, Morello-Frosch & Cushing, 2013; and Su et al., 2011). Therefore, policy decisions regarding the urban forest structure should, wherever possible, consider spatial differences and include local administrative scales and community impacts when making city and region-wide recommendations. The inclusion of local and community-based decision-making may help to avoid unintended consequences of urban greening such as a loss of affordable housing resulting from neighbourhood gentrification (Jesdale et al. 2013; Su et al., 2011).

2. EXPLORE DIVERSE GREENING STRATEGIES TO MEET GREEN DENSITY NEEDS IN URBAN AREAS.

Evidence shows that "more green is better" and in some cases suggests optimal urban greening densities of up to 50 per cent coverage or more (Ng et al., 2012). However, this may be challenging due to space constraints. Some planning models, such as the *Greening Master Plan* in Hong Kong, have set a 20 to 30 per cent green coverage target (Ng et al., 2012). To achieve density goals, several strategies are suggested including: 1.) The establishment of urban greenbelts, greenways and other protected green space in cities and suburbs. For example, Ontario's renowned Greenbelt is in the process of being expanded to protect urban river valleys in Toronto and neighbouring cities (Ontario Greenbelt Alliance 2013). 2.) Minimizing distances between small urban parks to maximize the effect of park cool islands and increase the flow of cool air and air-pollution dispersion (Tallis et al., 2011) 3.) Including minimum green densities for new site developments, including green roofs. For example, the City of Toronto passed a bylaw in May 2009 requiring construction of green roofs on 20 to 60 per cent of available roof space on all new buildings with a gross floor area of 2,000 square metres or more (Rinner & Hussain, 2011) and, 3.)Maximizing greening alternatives, such as green walls, where ground space is limited (Cameron et al., 2014; Koyama et al., 2013).

3. WHERE POSSIBLE, CONTINUE TO PROVIDE COST-BENEFIT ANALYSIS TO SUPPORT PROGRAM PLANNING.

Although cost-benefit analysis of urban greening is mired with complexities, it is frequently identified as critical for policy action (McPherson et al., 2011). Costs such as planning, site preparation, plant production, planting, stewardship, monitoring, outreach and administration are significant. Comparing these costs to evidence of benefits of green space such as PM reduction alone is not very useful since green spaces provide countless other benefits that need to be considered. These benefits include relief from heat stress, reduced urban heat island effects and stormwater runoff, and reductions in greenhouse gas emissions, energy consumption and morbidity and mortality rates that are only just beginning to be quantified (Mackey, Lee & Smith, 2012). Despite these challenges, the first national estimates on air quality and human health benefits of trees by Nowak et al. (2014) demonstrate the potential for integrating regional data on green space, weather, populations and pollution data with human health effects and costs. While these types of models have limitations, they are important for providing a more comprehensive understanding of the economic role of green space in protecting human health. Monitoring existing programs would also be beneficial (Tallis et al., 2011). Examples include the Million Trees LA program in Los Angeles (McPherson et al., 2011); Greening Master Plan in Hong Kong (NG); neighbourhood programs such as the Woodlands' tree protection policy (Sung, 2013); the Greening the Gateway initiative in London, linking multi-purpose green space across the city (Tiwary et al., 2009); and the Mile High Million program in Denver (Curtis et al., 2014).

4. PRIORITIZE VULNERABLE AREAS IN PLANTING STRATEGIES.

Vegetation screens and barriers between high pollution areas such as busy roadways and vulnerable areas such as playgrounds, schools, hospitals and residential areas should be prioritized (Escobedo & Nowak, 2009; Kocic et al., 2014; Saeobo et al., 2012; Steffens et al., 2012). However, pollution-barrier strategies could result in increased pollution levels within the street canyon and increase exposure for pedestrians and cyclists. Pugh et al. (2012) recommend that the use of street trees should be considered on a case-by-case basis. For streets with low traffic, trees are beneficial (Pugh et al., 2012). In areas where traffic is high, tree planting should be considered more cautiously through the use of modelling that includes tree species (including BVOC emissions of trees), canopy volume, canyon geometry and wind speed and direction (Escobedo & Nowak, 2009; Pugh et al., 2012).

5. MORE THAN GREENING IS REQUIRED; INTEGRATED POLICIES TO MITIGATE HEAT AND AIR POLLUTION ARE NEEDED

Many study authors emphasize that heat and air-pollution mitigation initiatives through increased greening alone are insufficient for achieving urban climate and air-quality goals. Overall air pollution reductions from green space are small relative to city-based emissions (Baro et al., 2014). Therefore, local urban greening should be integrated with strong regulatory approaches to pollution mitigation to achieve overall air-quality targets in cities (Baro et al., 2014).

AREAS FOR FUTURE RESEARCH

Due to the breadth of research explored, it is not possible to provide an exhaustive list of research gaps across the many research disciplines represented in this review. However, some general areas for future research have been identified to support urban green space policy and program planning.

1. STRONGER LINKS TO HEALTH.

Although there is a large and growing evidence base on the impacts of heat and air pollution on human health, as well as separate studies on heat and air-pollution mitigation from green space, few studies directly associate observed pollution or heat mitigation from green space with direct health impacts. This review has identified several recent studies that link ecosystem services with direct human health benefits in economic terms, but there are few specific epidemiological studies. Further research is needed to understand the physical, psychological, social and economic benefits from reduced heat and air pollution associated with green space. For example, research on the relationship between neighbourhood green space and heat-related stress and illness would be beneficial.

2. CANADIAN-BASED RESEARCH.

Only two Canadian studies were identified in this review. Only one study from Finland has explored air pollution mitigation from trees in winter. It found that models used to estimate pollution mitigation from trees might not apply to the winter of northern (Df) climates like Canada (Setala et al., 2013). There is a need for more Canadian-based investigation into the direct and indirect health benefits of green space across local and regional scales.

3. EQUITY ANALYSIS.

Emerging evidence for the uneven distribution and quality of green space and associated health inequalities related to burdens of heat and air pollution require greater attention. Research to understand and address possible inequities that result in greener environments for some urban communities and not others is important for improving health equity in cities.

4. EXAMINE WAYS TO ADDRESS THE CHALLENGES OF ROAD-TRAFFIC BARRIERS AND STREET-CANYON DESIGNS.

Although green barriers my be useful in protecting local communities from traffic emissions, many uncertainties remain in terms of how best to green street canyons, including the effect of different canyon geometries, vegetation types, wind speeds, deposition velocities of air pollutants, etc. Exploring alternative greening strategies may be helpful. For example, Wania et al. (2012) suggest that bushes instead of trees may retain more particles because they are closer to pollution sources and reduce concentrations at the height of the human respiratory tract.

REVIEW LIMITATIONS

The review is limited to studies published from 2009 to October 2014. The findings within this date range may not represent the full range of variables or findings using a broader date range. In addition, the search terms used may not have captured the full range of relevant studies, including possible negative impacts or trade-offs associated with green space, such as exposure to pollen and physical injuries.

The vast heterogeneity of study disciplines, methods, topics and designs makes direct comparisons of findings difficult and so this review maps and synthesizes overall findings, trends, gaps and contradictions. Articles were appraised and accepted into the review if they met the criteria for credibility, transferability and dependability (see Methods). Further assessment for bias or evidence strength based on each study method (i.e., modelling design, etc.) is beyond the scope of this review.

The green space scales and types described in this review do not represent distinct categories. There are many possible areas of overlap when comparing the effects of green space types and scales. Due to the breadth of the review, modifying variables are identified and discussed in general terms. For example, wind generally increases air-pollution mitigating effects of green space; however, other factors such as the built urban form may alter this relationship. An in-depth examination of the confluence of all modifying variables is beyond the scope of this review. The purpose of this report is to map and summarize the findings on urban green space, heat and air quality to inform public health policy and planning. This report does not summarize findings on the methodological challenges to researching urban green space, heat and air quality.

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Credit Valley Conservation
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APPENDIX A: WORKS CITED

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APPENDIX B: STUDIES REVIEWED

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APPENDIX C: DATA EXTRACTION FORM

2.1 ☐ Reviewer 1 ☐ Reviewer 2

2.2 Citation:

2.3 Year of publication:

2.4 City/cities:

2.5 Country:

2.6 Urban setting (if specified)

☐ urban ☐ periurban ☐ other______

2.7 Study method (choose only one)

☐ **Observational case study**
☐ ground-level data collection **(**Information collected in the field)
☐ remote sensing data collection
☐ modelling
☐ other (please specify) ______

☐ **Experimental**
☐ case control
☐ other (please specify) ______

☐ **Systematic review**

2.8 Indirect health impact explored

☐ heat mitigation
☐ thermal comfort (i.e., ambient temp) ☐ urban heat island (i.e., surface temps)
☐ other (please specify)_____

☐ air pollution mitigation
☐ volatile organic compounds (VOC) ☐ biogenic (BVOC)
☐ nitrogen dioxide (NO2) ☐ particulate matter (PM) ____
☐ carbon monoxide (CO) ☐ carbon dioxide (CO2)
☐ ozone (O3) ☐ sulfur dioxide (SO2)
☐ other ______ ☐ not specified ______
☐ multiple pollutants (please specify)______

2.9 Scale of green space examined (*scales drawn from Haase et al., 2014*)

☐ single site (small park, green roof, tree stand, etc.)
☐ multiple single sites: ___________
☐ neighbourhood scale

☐ entire city or town
☐ region
☐ comparison of scales ______
☐ other ___________________

2.10 Scale of impact examined (if specified)

☐ within green space site
☐ to adjacent non-green area
☐ neighbourhood level
☐ city level
☐ regional level
☐ comparison (specify) ______

2.11 Temporal scale (if specified)

☐ single point in time
season: ☐ spring ☐ summer ☐ fall ☐ winter
time: ☐ morning ☐ afternoon ☐ evening
☐ time series (please specify)______
☐ comparison by season________ time of day ______
☐ not specified ☐ other _____________________

2.12 Green space type (choose one) (include short description in space below if needed)

☐ green roof ☐ living wall ☐ community garden ☐ small park
☐ large park ☐ naturalized area ☐ neighbourhood green space (mixed)
☐ urban trees (as per *Roy et al., 2012)*
☐ street trees ☐ community trees ☐ private trees
☐ comparison of types ______ ☐ other ______

Description:

2.13 Vegetation type (include species types if specified)

☐ tree ______ ☐ grass ______ ☐ shrub______ ☐ other______
☐ comparison of types ______

2.14 Vegetation characteristics (if specified) (include a brief description for each box checked)

☐ vegetation size______ ☐ vegetation density ______ ☐ leaf area ______
☐ comparison_________ ☐ other______

2.15 Was air pollution mitigation documented in relation to the green space under study? Skip this question if the study was not on air quality/pollution.

☐ Yes ☐ No if yes, be sure to document findings in narrative section

2.16 Was heat mitigation documented in relation to the green space under study? Skip this question if the study was not on heat mitigation

☐ Yes ☐ No if yes, be sure to document findings in narrative section

2.17 Were any modifying variables identified in the study? For example, wind, season, time of day, climate, surrounding infrastructure?

☐ Yes ☐ No if yes, be sure to document findings in narrative section

2.18 Were any negative impacts or trade-offs identified in the study? For example: BVOC exposure, reduced visibility near roadways, allergies

☐ Yes ☐ No if yes, be sure to document findings in narrative section

2.19 Were any health benefits directly associated with the observed heat or air pollution mitigation from green space?

☐ Yes ☐ No if yes, be sure to document findings in narrative section

2.20 Narrative account of article: limit to one paragraph per questions (4 sentences plus relevant statistics)

2.20.1 Study purpose (highlight data gap the study is trying to fill if stated)

2.20.2 Key findings.

2.20.3 Study implications

2.20.4 Study limitations

2.20.5 Policy implications or initiatives cited (list any current initiatives if mentioned)

Studies in climates relevant to Canada were included in the review. For example, studies from warm temperate climates are relevant to summer conditions in many Canadian provinces. Using the Köppen Climate Classification System, studies from locations in Warm Temperate Climates (type C), Snow

APPENDIX D: CLIMATE CLASSIFICATIONS

Climates (type D) and Polar Climates (Type E) were included in the review. Studies from Equatorial (Tropical) Climates (Type A) and Arid Climates (Type B) were excluded (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006).

Climate classifications	
(Type C) Warm temperate climates	Cs - Warm temperate climate with dry summer (e.g., Mediterranean) Cw - Warm temperate climate with dry winter Cf - Warm temperate climate, fully humid (aka humid subtropical)
(Type D) Snow climates	Ds - Snow climate with dry summer Dw - Snow climate with dry winter Df - Snow climate, fully humid
(Type E) Polar climates	ET - Tundra climate EF - Frost climate

APPENDIX E: KEY TERMS AND DEFINITIONS

Albedo – the ratio of reflected to incident radiation at a particular surface or combination of surfaces, over all the wavelengths of solar irradiation (Taha et al., 1988).

Biogenic Volatile Organic Compounds (BVOC) – organic atmospheric trace gases other than carbon dioxide and monoxide, including isoprenoids, alkanes, alkenes, carbonyls, alcohols, esters, ethers and acids (Kesselmeier & Staudt, 1999). Plants, in particular trees, emit a considerable amount of BVOCs (Calfapietra, 2013).

Celsius (C) – a scale or unit of temperature in terms of its difference from 273,15 K, the ice point (Preston-Tomas H, 1990).

Evapotranspirative cooling **–** the process by which plants release water into the surrounding air and thereby reduce ambient temperatures (Taha, 1998).

Green roof – a roof of a building partially or completely covered with vegetation and a growing medium (i.e., soil) that is planted over a waterproof membrane.

Green space – any form of semi-natural environment (e.g., parks, green roofs) or plant species (e.g., trees) in urban areas, including urban forests (Bowler et al., 2010).

Heat wave – daily temperatures occurring over several consecutive days above the normal weather and temperature patterns for a region (Oudin Åström et al., 2011).

Heat stress / thermal stress – heat stress occurs when hot and humid conditions overcome the human body's natural cooling system. They can be fatal. Syptoms include cramps, fainting, serious heat exhaustion and heat stroke (Government of Ontario, 2012).

Impervious surface – any material that prevents the infiltration of water into soil (Arnold & Gibbons, 1996).

Kelvin (K) – the unit of physical quantity known as thermodynamic temperature (T) is the kelvin, defined as the fraction 1/273,16 of the thermodynamic temperature of the triple point of water (Preston-Tomas, H., 1990).

Large urban park **–** defined in this review as an urban park over one hectare in size. A park was categorized as large if it was referred to as a large or reported to be over one hectare.

Living wall – planted vegetation on the inside or outside wall of an urban building.

Leaf Area Density (LAD) – the ratio of leaf surface area to total volume occupied by a vegetative element (Steffens et al., 2012).

Mean radiant temperature (MRT) – the uniform temperature of an imaginary enclosure, in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure (ASHRAE, 2001).

Mixed neighbourhood green space – defined in this review as mixed areas of neighbourhood grass, trees or other vegetation not categorized as a park.

Normalized Difference Vegetation Index (NDVI) – a graphical indicator used to assess remotely sensed data to measure vegetation amount (Crippen, 1990).

Park cool island (PCI) – an irregular pattern of cooler areas nested within generally warmer urban areas, created by shading and evapotranspirational cooling and extended to the air above non-vegetated areas through advective cooling (Chow et al., 2011).

Patch density (PD) – equals the number of patches of a specific land-cover class divided by total landscape area (Herold et al., 2003).

Particulate matter (PM) – a mixture of solid particles and liquid droplets in the air, including aerosols, smoke, fumes, dust, ash and pollen. Coarse particulate matter (PM10) is emitted from residential heating sources and power plants, whereas fine PM2.5 comes from cars, utilities and wood burning (Shah & Balkhair, 2011).

Physiological equivalent temperature (PET) – thermal comfort index for assessing comfortable air temperatures for people in relation to the temperature of the human body (Höppe, 1999).

Percent cover of greenspace (PLAND) – PLAND equals the sum of the areas (m2) of a specific land-cover class divided by total landscape area, multiplied by 100 (Herold et al., 2003).

Scale. Two types of scale were examined in this review:

1. *Scale of green space.* The area or size of green space under study, where specified. This includes: a) a single site (small park, green roof, tree stand, etc.); b) multiple single green space sites; c) neighbourhood-level greenspace (i.e., NDVI of a neighbourhood); d) city-level green space (i.e., area of an urban forest); and e) regional-level green space (multiple urban forests).

2. *Scale of impact.* The impact area under study where specified. This includes: a) impact within green space site b) impact to adjacent non-green area; c) neighbourhood-level impact; d) city-level impact and e) regional-level impact. (Scales adapted from Haase et al., 2014)

Small urban park – for this review a small urban park is defined as a public urban park or square less than one hectare. A park was categorized as small if it was referred to as "small" or reported to be under one hectare.

Street canyon (also known as an urban canyon) – a place where the street is flanked by buildings on both sides, creating a canyon-like environment (Vardoulakis et al., 2003).

TMRT or MRT – mean radiant temperature (MRT) is defined as the area-weighted mean temperature of all the objects surrounding the human body. Often used to understand thermal comfort (Magnum & Hill, 1977).

Thermal comfort – the narrow range in which environmental conditions that provide thermal satisfaction, dependent upon the activity of the subjects and their clothing level, allow people to maintain a constant core body temperature of 37^{0}C (Nikolopoulou et al., 2001).

Urban – town or city setting, including suburban and peri-urban settings.

Urban forest – the sum of all urban trees, shrubs, lawns and pervious soils in an urban setting (Escobedo et al., 2011).

Urban trees – urban trees include trees found in urban spaces other than a park or forested area. They can include street trees, trees in public community areas other than parks and trees in backyards and other private properties (Roy et al., 2012).

Vegetation fraction (VF) – the percentage or fraction of occupation of vegetation canopy in a given ground area in vertical projection (Li et al., 2011).

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