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Air pollution removal by urban forests in Canada and its effect on air quality and human health

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ABSTRACT

Urban trees perform a number of ecosystem services including air pollution removal, carbon sequestration, cooling air temperatures and providing aesthetic beauty to the urban landscape. Trees remove air pollution by intercepting particulate matter on plant surfaces and absorbing gaseous pollutants through the leaf stomata. Computer simulations with local environmental data reveal that trees in 86 Canadian cities removed 16,500 tonnes (t) of air pollution in 2010 (range: 7500–21,100 t), with human health effects valued at 227.2 million Canadian dollars (range: $52.5–402.6 million). Annual pollution removal varied among cities and ranged up to 1740 t in Vancouver, British Columbia. Overall health impacts included the avoidance of 30 incidences of human mortality (range: 7–54) and 22,000 incidences of acute respiratory symptoms (range: 7900–31,100) across these cities.

1. Introduction

Air pollution is a significant problem globally that affects human health and well-being, ecosystem health, crops, climate, visibility and man-made materials. Common air pollutants include carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), sulfur dioxide (SO_2), and particulate matter less than 2.5 µm ($PM_{2.5}$) and 10 µm (PM_{10}) in aerodynamic diameter. In Canada, air quality standards have been developed for $PM_{2.5}$ and O_3, and work has begun to develop standards for NO_2 and SO_2 (Canadian Council of Ministers of the Environment (CCME), 2016). Health effects related to air pollution include impacts on pulmonary, cardiac, vascular, and neurological systems (e.g., Pope et al., 2002). Outdoor air pollution, mostly $PM_{2.5}$, is estimated to lead to 3.3 million premature deaths per year worldwide, mainly in Asia (Lelieveld et al., 2015). In Canada it is estimated that there are 21,000 premature deaths attributable to air pollution each year (Canadian Medical Association, 2008).

Trees and forests affect air quality through the direct removal of air pollutants, altering local microclimates and building energy use, and through the emission of pollen, which affects allergies (e.g., Ogren, 2000) and volatile organic compounds (VOCs), which can contribute to O_3 and $PM_{2.5}$ formation (e.g., Chameides et al., 1988). However, integrative studies have revealed that trees, particularly low VOC emitting species, can be a viable strategy to help reduce urban O_3 levels (e.g., Taha, 1996; Nowak et al., 2000).

Trees remove gaseous air pollution primarily by uptake via leaf stomata, though some gases are removed by the plant surface. Once inside the leaf, gases diffuse into intercellular spaces and may be absorbed by water films to form acids or react with inner-leaf surfaces. Trees directly affect particulate matter in the atmosphere by intercepting particles, emitting particles (e.g., pollen) and resuspension of particles captured on the plant surface. Some particles can be absorbed into the tree, though most intercepted particles are retained on the plant surface. The intercepted particles often are resuspended to the atmosphere, washed off by rain, or dropped to the ground with leaf and twig fall (Smith, 1990). During dry periods, particles are constantly intercepted and resuspended, in part, dependent upon wind speed. The accumulation of particles on the leaves can affect photosynthesis (e.g., Darley, 1971) and therefore potentially affect pollution removal by trees. During precipitation, particles can be washed off and either dissolved or transferred to the soil. Consequently, vegetation is only a temporary retention site for many atmospheric particles, where particles are eventually moved back to the atmosphere or moved to the soil. Pollution removal by urban trees in the United States has been estimated at 651,000 tonnes (t) per year (Nowak et al., 2014).

While various studies have estimated pollution removal by trees (e.g., Nowak et al., 2006a, 2014, McDonald et al., 2007, Tallis et al., 2011), most studies on pollution removal do not directly link the removal with improved human health effects and associated health

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values. A few studies that have linked removal and health effects include a study in London, England where a 10 × 10 km grid with 25% tree cover was estimated to remove 90.4 t of PM_{10} annually, which equated to the avoidance of 2 deaths and 2 hospital admissions per year (Tiwary et al., 2009). In addition, Nowak et al. (2013a) reported that the total amount of $PM_{2.5}$ removed annually by trees in 10 U.S. cities in 2010 varied from 4.7 t in Syracuse to 64.5 t in Atlanta. Estimates of the annual monetary value of human health effects associated with $PM_{2.5}$ removal in these same cities (e.g., changes in mortality, hospital admissions, respiratory symptoms) ranged from $1.1 million in Syracuse to $60.1 million in New York City. Mortality avoided was typically around 1 person per year per city, but was as high as 7.6 people per year in New York City. Trees and forests in the conterminous United States removed 17.4 million tonnes (t) of air pollution in 2010 with human health effects valued at 6.8 billion U.S. dollars (Nowak et al., 2014). Most of the pollution removal occurred in rural areas, while most of the health impacts and values were within urban areas. Health impacts included the avoidance of more than 850 incidences of human mortality and 670,000 incidences of acute respiratory symptoms.

As people and trees exist throughout a landscape in varying densities, not only will pollution removal and its effects on local pollution concentrations vary, but so will the associated human health impacts and values derived from this ecosystem service. While studies have been conducted on individual Canadian cities (e.g., McNeil and Vava, 2006, TRCA, 2011, City of Edmonton, 2012, Nowak et al., 2013b), a consistent assessment across all Canadians cities of removal of key air pollutants by urban trees has not yet been completed. Such an analysis will allow for a greater understanding of the services provided by green urban infrastructure and set a baseline for investigating changes in service provision over time. The objectives of this paper are to estimate the amount of air pollution (CO, NO_2, O_3, $PM_{2.5}$, SO_2) removed by trees within 86 Canadian cities in 2010 and its associated monetary value and impact on human health.

2. Methods

To estimate avoided health impacts and associated dollar benefits of air pollution removal by trees in 86 Canadian cities (Suppl. 1) in 2010, four types of analyses were conducted to estimate: 1) the total tree cover and leaf area index on a daily basis to account for seasonal variability, 2) the hourly flux of pollutants to and from the leaves, 3) the effects of hourly pollution removal on pollutant concentration in the atmosphere, and 4) the health impacts and monetary value of the change in NO_2, O_3, $PM_{2.5}$ SO_2, and CO concentration. City areas were delimited using shape files provided by Environment and Climate Change Canada and were based on the Statistics Canada populated places boundary file (Statistics Canada, 2011a). It is important to note that the boundaries used are based on a combination of population densities, roads and other geographic data sets and are often not the same as the administrative municipal boundaries. As a result, population counts, area extents and tree coverage may differ from those reported by municipal or other agencies. To simplify presentation, only data from the 15 most populated cities are presented (Table 1), but results for all 86 cities can be found in the supplemental materials.

2.1. Tree cover and leaf area index

Percent and hectares of tree cover within each city were derived from photo-interpretation of aerial images (c. 2011) as detailed in Pasher et al. (2014) (Table 1). Maximum (mid-summer) leaf area index (LAI: m^2 leaf area per m^2 projected ground area of canopy) values were derived from the level-4 MODIS/Terra global Leaf Area Index product for the 2011 growing season (U.S. Geological Survey (USGS), 2013) based on an average of all maximum pixel values within the city. In areas where LAI values per unit of tree cover were missing or abnormally low, a midsummer LAI value of 4.9 was used based on the average LAI in urban areas (Nowak et al., 2008).

Table 1
City area (km^2), human population in 2011 (Statistics Canada, 2011b), percent tree cover (%TC) and percent evergreen cover (%EG) for the 15 most populated cities. These cities comprise over 75% of the urban population and 60% of the total urban area in Canada.

City	Province	Area	Population	%TC	%EG
Calgary	Alberta	722.8	1,095,404	9.3	3.8
Edmonton	Alberta	872.6	960,015	13.0	3.8
Gatineau	Quebec	172.3	302,728	30.6	6.0
Halifax	Nova Scotia	291.4	297,943	51.8	16.8
Hamilton	Ontario	394.8	670,580	21.6	7.3
Kitchener	Ontario	319.4	444,681	20.5	7.3
London	Ontario	225.7	366,191	20.3	7.3
Montréal	Quebec	1557.6	3,407,963	22.7	6.0
Ottawa	Ontario	389.4	933,596	26.5	6.0
Québec	Quebec	682.9	696,946	47.0	6.0
St. Catharines – Niagara	Ontario	394.4	309,319	23.9	7.3
Toronto	Ontario	1763.4	5,132,794	18.2	7.3
Vancouver	British Columbia	1206.6	2,135,201	40.0	2.1
Victoria	British Columbia	281.6	316,327	45.5	2.1
Winnipeg	Manitoba	460.1	671,551	16.5	12.3

Percent tree cover classified as evergreen was estimated based on the average percent evergreen species for the regional forest type (Table 1, Suppl. 1). LAI values were combined with percent evergreen information and local leaf-on and leaf-off (frost) dates (National Climatic Data Center (NCDC), 2005) to estimate total daily leaf surface area in each city assuming a four-week transition period centered on leaf-on and leaf-off dates for spring and autumn, respectively.

2.2. Pollution removal by trees

Hourly pollution removal or flux (F in μg m^{-2} h^{-1}) was estimated as:

$$F = V_d \times C$$

Where V_d is the deposition velocity of the pollutant to the leaf surface (m hr^{-1}) and C is pollutant concentration (μg m^{-3}) (e.g., Hicks et al., 1989). Hourly concentrations for each pollutant by city were obtained from Environment and Climate Change Canada for the year 2010 (Environment Canada, 2013). Missing pollutant data were filled in based on procedures described in Hirabayashi and Kroll (2017). The average percent missing pollution data were 9.6 percent for NO_2, 8.3 percent for SO_2, 6.9 percent for $PM_{2.5}$, 6.6 percent for CO and 5.3 percent for O_3. For PM data, if hourly data did not exist, then daily and 6-day measurements were used to represent the hourly concentration values throughout the day (i.e., the average daily value was applied to each hour of the day). If multiple monitors existed within a city for the same pollutant, the average hourly value was used. If no pollutant monitors existed within the city, the closest data monitor was assigned to represent that area. The median distance away from city center was 35 km for CO, 21 km for SO_2, 11 km for NO_2 and 7 km for O_3 and $PM_{2.5}$.

To calculate the hourly deposition velocity, local hourly weather data for 2010 from the National Climatic Data Center (National Climatic Data Center (NCDC), 2013) were used. If no weather data existed within the city, the closest monitor data was assigned to represent that area. If more than one monitor existed, the weather data closest to the geographic center of the area was used. The median distance from city center was 24 km, with 12 of the 85 cities having weather stations over 100 km away (maximum distance was 271 km from Moose Jaw).

Deposition velocities for all pollutants and resuspension rates for particulate matter were calculated using the i-Tree model (www.itreetools.org) based on methods detailed in Nowak et al. (2006a, 2013a) and Hirabayashi et al. (2011, 2012). Total removal of a pollutant in a city was calculated as the annual flux value (μg m^{-2} yr^{-1}) times total tree cover (m^2). Minimum and maximum estimates of removal were based on the typical range of published in-leaf dry deposition velocities (Lovett, 1994).