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Review of plants to mitigate particulate matter, ozone as well as nitrogen dioxide air pollutants and applicable recommendations for green roofs in Montreal, Quebec☆

Shannon Gourdji

McGill University, 21111 Lakeshore Road, Sainte-Anne-de-Bellevue, QC H9X 3V9, Canada

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ABSTRACT

In urbanized regions with expansive impervious surfaces and often low vegetation cover, air pollution due to motor vehicles and other combustion sources, is a problem. The poor air quality days in Montreal, Quebec are mainly due to fine particulate matter and ozone. Businesses using wood ovens are a source of particulates. Careful vegetation selection and increased green roof usage can improve air quality. This paper reviews different green roofs and the capability of plants in particulate matter (PM), ozone (O_3) as well as nitrogen dioxide (NO_2) level reductions. Both the recommended green roof category and plants to reduce these pollutants in Montreal's zone 5 hardiness region are provided. Green roofs with larger vegetation including shrubs and trees, or intensive green roofs, remove air pollutants to a greater extent and are advisable to implement on existing, retrofitted or new buildings. PM is most effectively captured by pines. The small *Pinus strobus* 'Nana', *Pinus mugho* var. *pumilio*, *Pinus mugho* 'Slowmound' and *Pinus pumila* 'Dwarf Blue' are good candidates for intensive green roofs. Drought tolerant, deciduous broad-leaved trees with low biogenic volatile organic compound emissions including Japanese Maple or *Acer palmatum* 'Shaina' and 'Mikawa-Yatsubusa' are options to reduce O_3 levels. Magnolias are tolerant to NO_2 and it is important in their metabolic pathways. The small cold-tolerant *Magnolia* 'Genie' is a good option to remove NO_2 in urban settings and to indirectly reduce O_3 formation. Given the emissions by Montreal businesses' wood ovens, calculations performed based on their respective complex roof areas obtained via Google Earth Pro indicates 88% *Pinus mugho* var. *pumilio* roof coverage can annually remove 92.37 kg of PM_{10} of which 35.10 kg is $PM_{2.5}$. The removal rates are 4.00 g/m^2 and 1.52 g/m^2 for PM_{10} and $PM_{2.5}$, respectively. This paper provides insight to addressing air pollution through urban rooftop greening.

1. Introduction

Globally, air pollution is a widespread dilemma due to its impacts on both human and environmental well-being (Kampa & Castanas, 2008). Urban areas often have the highest levels of air pollution (Jim & Chen, 2008; Nowak et al., 2006; Nowak et al., 2014). This pollution occurs mainly due to anthropogenic activities (Kampa & Castanas, 2008; Speak et al., 2012). Air pollution in urban areas impacts human health (Nowak et al., 2014). Particulate matter or PM (Freer-Smith et al., 2004) and especially fine particulate matter or $PM_{2.5}$, with an aerodynamic diameter less than 2.5 μm, has been strongly related to adverse health impacts (Brauer et al., 2012). $PM_{2.5}$ affects the vascular and respiratory systems (Freer-Smith et al., 2004). In 2005, 89% of the global population resided in regions where the annual 10 μg/m^3 $PM_{2.5}$ average World Health Organization Air Quality Guideline was exceeded (Brauer et al., 2012). Gaseous ozone or O_3 and nitrogen dioxide or NO_2 pollutants can also impact the respiratory system (Kampa & Castanas, 2008). North America was amongst the top five global regions with the most elevated seasonal O_3 levels, out of the twenty-one investigated regions (Brauer et al., 2012).

Other effects of air pollution include decreased visibility as well as ecosystem and crop impacts. PM is the main air pollutant that reduces visibility by scattering and absorbing light. Nitrate particles, forming from the photoxidation of NO_x such as NO_2, can lead to decreased visibility as well. PM accumulation in soil (Beckett et al., 1998) can affect its composition leading to further potential environmental impacts. Atmospheric reactions involving NO_2 can

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E-mail address: shannon.gourdji@mail.mcgill.ca.

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lead to the formation of nitric acid (Teklemariam & Sparks, 2006) or acid rain that can adversely affect ecosystems. Elevated O_3 levels have been noted to decrease yields in certain crops (Fares et al., 2010). However, there are plant species specific differences with respect to tolerance to air pollutants (Jim & Chen, 2008).

In Montreal, Quebec the 2016 air quality report revealed the occurrence of 29 poor air quality days which were associated with $PM_{2.5}$ levels surpassing 35 μg/m^3, over a minimum 3 h period, at any monitoring station. Out of these poor air quality days, 8 were smog days. These smog days were characterized by $PM_{2.5}$ that exceeded 35 μg/m^3, over a minimum of 3 h, across over 75% of the Montreal region. Such smog days are often associated with high levels of PM over 24 h or even longer timeframes (City of Montreal, 2017).

In Montreal, the air pollutants that cause these poor air quality days are primarily $PM_{2.5}$ as well as O_3. The transportation, residential wood combustion, industrial and commercial wood combustion sectors emitted 818, 701, 241 and 59 tons of $PM_{2.5}$ respectively, in 2014 (City of Montreal, 2015). Montreal's 2014–2016 average $PM_{2.5}$ level of 8.6 μg/m^3 was both below Canada's 2020 and the World Health Organization's standards of 8.8 and 10 μg/m^3 respectively. However, further improvements would still be beneficial as there is not any identified threshold under which this pollutant won't affect health (City of Montreal, 2017). Similarly, the 2014–2016 daily O_3 average of the fourth highest value of 56 ppb is under the 2020 standard of 62 ppb (City of Montreal, 2017), yet this still adds to the number of poor air quality days. Additionally, NO_2 can indirectly lead to poor air quality days in Montreal by reacting with volatile organic compounds under the sun's ultra-violet radiation to form O_3 (Fares et al., 2010).

Increased vegetation cover and emphasis on appropriate plant selection can help mitigate some of the effects of air pollution. PM air pollutants are often deposited on plants due to their high surface area to volume ratio (Janhäll, 2015). However, attributes that are species dependent including leaf texture, orientation, rigidity as well as cuticle make-up and form can impact the level to which the particulates are absorbed by the plant or remain on its surface. Increased time periods of PM on plant surfaces can lead to photodegradation of the pollutant (Terzaghi et al., 2013). However, PM may re-enter the atmosphere due to windy conditions or get dissolved into the soil matrix due to a precipitation event (Nowak et al., 2014). Air pollutants such as O_3 and NO_2 can enter leaves through the stomata. These gaseous compounds are subsequently diffused within intercellular spaces and can further react with leaf components. Alternatively, O_3 and NO_2 may be absorbed by water present within the leaves (Nowak et al., 2014).

Plants can additionally serve to indirectly reduce air pollution (Yang et al., 2005). They have the ability to impact climate conditions at a local scale. Plants' evapotranspiration and ability to provide shade will decrease air temperatures thus minimizing the production of some air pollutants associated with building cooling energy requirements (Yang et al., 2005) in various urban areas.

Impervious surfaces usually cover more than 60% of urban land area (Akbari et al., 2009). Roofs alone often make up 20 (Akbari et al., 2009; Currie & Bass, 2008) to 25% of all urban surfaces (Akbari et al., 2009). This roof area provides the opportunity to grow plants to help mitigate air pollution in urban areas, including Montreal, where there are already many competing land uses. Although traffic generated air pollutant concentrations tend to follow a negative vertical profile, green roofs are still considered a viable option to improve air quality because they can be directly incorporated into urban environments (Speak et al., 2012). Green roofs can be classified into one of three categories including intensive, extensive and semi-intensive. Each type of green roof has specific design requirements that impact plant selection and therefore, the potential of mitigating various air pollutants.

Intensive green roofs contain a growing medium with a depth in the 15–120 cm range (Kosareo & Ries, 2007). Intensive green roofs are suitable to grow large herbaceous vegetation, shrubs as well as small trees (Yang et al., 2008). Extensive green roofs have a growing substrate depth in the 5–15 cm range (Kosareo & Ries, 2007). These roofs are favourable to grow smaller, slow growing plants (Yang et al., 2008). Semi-intensive green roofs combine the attributes of both the intensive and extensive green roofs and are distinguished by having 25% of the growing medium under or over 15 cm (Yang et al., 2008). Semi-intensive roofs allow for the growth of more types of plants than extensive green roof systems but are not as diverse as intensive green roofs.

This paper will begin by investigating how green roof vegetation affects air pollution and the impacts of specific vegetation in reducing PM, O_3 as well as NO_2 pollutants based on the literature, prior to providing recommendations targeted to the Montreal region. The initial hypotheses of this paper were (1) that there would be differences amongst which plant species were the most effective in mitigating air pollution depending on the target pollutant and (2) that coniferous plants would be useful to mitigate air pollution in Montreal's climate.

2. Literature review: vegetation impacts

Recently, interest in green roofs has been increasing due to the benefits offered from vegetation, including air pollution mitigation, in urban settings. This section of the paper will highlight important findings from the literature on green roofs' ability to mitigate air pollution and the plants' ability to improve air quality with regards to PM, O_3 as well as NO_2 levels. Based on this literature review, future plant recommendations to help improve the urban air quality in Montreal, will be provided.

2.1. Green roofs and air pollution

While the literature has demonstrated that green roofs can reduce air pollution, only several studies have assessed the impact differences associated with growing different categories of plants (Currie & Bass, 2008; Yang et al., 2008) or species (Speak et al., 2012) on green roofs. Currie & Bass (2008) investigated the effects of trees, shrubs and grass on air pollutant removal in the midtown region of the Greater Toronto Area by using the Urban Forest Effects or UFORE model to provide different green roof scenarios. Air pollution levels, hourly meteorological information as well as current land use data were used in the model. The study found that intensive green roofs with shrubs would have a greater impact in removing air pollutants than extensive grass based green roofs. If baseline shrubs on the ground were supplemented with 20% intensive green roofs, these structures could remove 4.48, 1.74, 1.24 and 0.41 metric tons/year of PM_{10}, O_3, NO_2 and SO_2, respectively (calculated from Currie & Bass, 2008). In contrast, if baseline trees and shrubs on the ground were supplemented with 20% extensive green roofs only, 0.88, 1.27, 0.65 and 0.25 metric tons/year of PM_{10}, O_3, NO_2 and SO_2 would be removed. Although trees were not investigated as part of green roof structures, they were found to reduce air pollutants to the greatest degree due to their high surface area (Currie & Bass, 2008).

Yang et al. (2008) found the amounts of air pollutants that were removed by green roofs in Chicago and that would be removed by expanding the installations based on different vegetation categories. Current green roofs were surveyed and a dry deposition model determined the pollutant removal. Hourly pollution and meteorological data were used. In Chicago, the 19.8 ha of green