DEBATING SCIENCE

COURSE BLOG OF JUNIOR YEAR WRITING IN THE COLLEGE OF NATURAL SCIENCES AT THE UNIVERSITY OF MASSACHUSETTS AMHERST

GREEN ROOFS: AN ANALYSIS ON AIR POLLUTION REMOVAL AND POLICY IMPLEMENTATION

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In October 1948, a thick cloud of air pollution formed above the industrial town of Donora, Pennsylvania. It lingered for five days, killed 20 people and induced sickness in 43% of the town (Environmental Protection Agency, 2007). Pollution poses a serious threat to our environment and health. Nearly one-quarter of the people in the U.S. live in areas with unhealthy short-term levels of particle pollution, and roughly one in ten people live where there are unhealthful levels year-round (American Lung Association, 2010). Air pollution is of particular concern to public health as it is the

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cause of hazards including upper respiratory irritation, chronic respiratory irritation, heart disease, lung cancer, and chronic bronchitis (Kampa & Castanas, 2008). The most common health-related impacts from air pollution are increased occurrences of respiratory illnesses such as asthma and a greater incidence of cardiovascular disease (Pope, Bates & Raizenne, 1995). Urban environments struggle heavily with air pollution due to the large amount of factories and vehicles that are major sources of air pollutants that accumulate so much that they become a hazard to human health. In Canada, the Ontario Medical Association found air pollution to result in 9,500 premature deaths per year (OMA, 2008) and estimates increased costs of healthcare up to $506.64 million and lost productivity of up to $374.18 as a result of air pollution (OMA, 2005). Conditions will only worsen as pollution grows with population, traffic, industrialization and energy use (Mayer, 1999). There are many pollutants in the air of an urban environment, though particulate matter (PM10), ozone (O_3), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2) are among the most serious to human health (World Health Organization, 2016).

Particulate matter that appears in urban environments is made up of sulfate, nitrates, ammonia, sodium chloride, black carbon, mineral dust and water that exist in the air from human activities such as combustion of fossil fuels, vehicles, and factory emissions. According to The World Health Organization (WHO), the limit for PM10 is 50 $\mu g/m^3$ annual mean. This represents how much particulate matter is allowed in the air annually by law. Chronic exposure to particles contributes to the risk of developing cardiovascular, respiratory diseases, and lung cancer (WHO, 2017). In countries of Europe that have concentrations of PM above guideline levels, it is estimated that average life expectancy is 8.6 months lower than it would be if PM exposure from human sources was regulated (WHO, 2017).

NO2 is most commonly formed from anthropogenic burning of fuel (heating, power generation, and engines in vehicles/ships). The limit for nitrogen dioxide is 40 $\mu g/m^3$ annual mean. Epidemiological studies have shown that symptoms of bronchitis in asthmatic children increased in association with long-term exposure to NO_2 and at short-term concentrations above 200 $\mu g/m^3$, NO2 is a toxic gas which causes significant inflammation of the airways (WHO, 2017). Reduced lung function growth is also linked to NO_2 at higher concentrations currently measured in Europe and the US. The US EPA (1998) also focuses on the danger of NO2 by stating that Nitrogen oxides (NO_x) resulting from combustion of fossil fuels can form ground level ozone that causes respiratory problems, premature deaths, and reductions in crop yields. (EPA, 1998).

Ozone at ground level, not to be confused with the ozone layer in the upper atmosphere, is formed from vehicle and factory emissions and emissions from solvents and industry. The legal amount that is allowed in cities is 100 $\mu g/m^3$ 8-hour mean, which means that by law over 8 hours concentrations of ozone cannot exceed 100 μg per cubic meter of air. In some cases, chemicals like nitrogen oxides (NO_x) react with sunlight and also contribute to forms of ozone. The limit for ozone is 100 $\mu g/m^3$ 8-hour mean and once this threshold is passed, O3 can cause breathing problems, trigger asthma, reduce lung function and cause lung diseases (WHO, 2017). The American Lung Association (2007) reported that annually, over 3,700 premature deaths in the United States (premature death is a death that occurs before a person reaches their expected age) can occur as a result of a 10 parts per billion (ppb) increase in O_3 levels (ALA, 2007). Bell (2004) found that increased mortality rates in 95 urban areas within the US are linked to elevated levels in ozone, with one of these urban areas being Chicago, where ALA (2007) found over 2 million people at increased risk for health problems resulting from short-term exposure to O_3 and particulate matters (ALA, 2007; Bell, 2004).

SO_2 is a colourless gas with a sharp odour that is produced from the burning of sulfur-containing fossil fuels (coal/oil) for heating residences, generating power, and motor vehicles along with the smelting (extraction by melting) of mineral ores that contain sulfur. The limit for sulfur dioxide is 20 $\mu g/m^3$ 24-hour mean and this means that air in cities will contain on average 20 μg per cubic meter over the span of 24 hours. When the limit is exceeded, SO_2 can affect the respiratory system, lung functioning, and cause irritated eyes. Evidence shows that the effects of sulfur dioxide are felt very quickly and most people would feel the worst symptoms of coughing, wheezing, shortness of breath, or a tight feeling around the chest in 10 or 15 minutes after breathing it in (S02, 2005). Inflammation of the respiratory tract causes coughing, mucus secretion, aggravation of asthma and chronic bronchitis and makes people more prone to infections of the respiratory tract (WHO, 2017).

One policy the U.S. government has in place to control pollution levels is the Clean Air Act (CAA) of 1970 (majorly revised in 1977 and 1990). The CAA's purpose is to reduce air pollution and its harmful effects by setting limits on pollution. This Act requires states to meet specific air quality standards regarding six common pollutants: particulate matter, ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide, and lead (EPA, 2017b). The Act contains specific provisions to address hazardous or toxic air pollutants, acid rain, chemical emissions that deplete the ozone layer, and regional haze (EPA, 2017b). The six "criteria" air pollutants are regulated based primarily on human health and secondarily on environmental criteria.

The CAA improved the environment which in turn improved the economy and human health. In the 45 years following the installation of the CAA, national emissions of the six common pollutants dropped an average of 70% while gross domestic product grew by 246% (EPA, 2017c). Forty-one areas that previously had unhealthy carbon monoxide levels in 1991 now meet the health-based national air quality standard. In 1990 alone, pollution reductions under the Act prevented 205,000 early deaths, 10.4 million lost I.Q. points in children due to lead exposure, and a multitude of other health effects (Environmental Protection Agency, 2017d). Despite massive improvements in air quality since CAA took effect, millions of Americans still live in areas with pollution levels exceeding the limits (EPA, 2007). Those who struggle to meet CAA air quality standards may find green roofs a useful tool to bring pollutant levels down.

In response to rising air pollutants, people are considering transforming city rooftops into green roofs to mitigate the problem. A green roof is a layer of vegetation installed on top of a roof, either flat or slightly sloped (National Park Service, 2017). The high amount of rooftop space in urban cities creates an opportunity for green roofs to be implemented on a large scale. Roofs represent 21–26% of urban areas and 40–50% of their impermeable areas (Wong, 2005; Dunnett & Kingsbury, 2004). These spaces typically have much unused surface area that could be repurposed to combat the aforementioned effects of harmful air pollutants, a green roof's main purpose. The plants that compose the roof are able to take up compounds through their natural processes respiration and photosynthesis, which remove the pollutants from the air and improve its quality.WHO has guidelines for the limits of the primary air pollutants that must not be exceeded in urban environments. Green roofs will help keep the levels of PM10 at 50 $\mu g/m^3$ annual mean, nitrogen dioxide at 40 $\mu g/m^3$ annual mean, ozone at 100 $\mu g/m^3$ 8-hour mean, and the concentrations of sulfur dioxide in the air of urban environments at 20 $\mu g/m^3$ 24-hour mean.

Literature surrounding green roofs agrees on their impact of particulate matter removal (Speak, Rothwell, Lindley & Smith, 2012; Currie & Bass, 2008; Rowe, 2011; City of Los Angeles, 2005; Yang, Yu & Gong, 2008; Jayasooriya, Ng, Muthukumaran & Perera, 2017). The range of particulate that is annually reduced by a green roof is 0.42–3.21 g/m2 over 500,000 square meters of rooftops (Speak et al, 2012). Rowe (2011) performed a study where 2000 m^2 of uncut grass were planted on a green roof. It was estimated that the green roof could remove up to 4000 kg of particulate matter. In a simulation where green roofs were built over 198,000 square meters of roofs in Chicago, 234.5 kg of particulate matter would be removed by green roofs in one year (Yang et al., 2008). Yang et. al (2008) also did a study where the concentrations of acidic gaseous pollutants and particulate matters on a 4000 m^2 roof in Singapore are measured before and after the installation of a green roof. Research found that the levels of particulate matter was reduced by 6% in the air above the roof after installation of the green roof (Yang et al., 2008). Jayasooriya et al. (2017) state that green roofs annually remove 1.53 g/m2 PM_{10} (Jayasooriya et al., 2017).Currie and Bass (2008) state that green roofs have the potential to reduce annual amounts of PM_{10} by .89–9.21 g/m2 (grams per square meter) over 486,000-2,430,000 square meters of green roof coverage in Toronto (Currie & Bass, 2008). Jayasooriya et al. (2017) states that green roofs annually remove 1.53 g/m2 PM_{10} (Jayasooriya et al., 2017). Another study on green roof remediation in Los Angeles (LA) puts these numbers of removed particulate matter into context. The city of LA found one square meter of green roof able to remove approximately 0.1 kg of particulate matter per year and if a gasoline powered vehicle were to release .01 grams of pm per mile of travel and drive 10,000 miles per year, then the vehicle would emit 100 grams per year (.01 kg/year) and therefore, one square foot of green roof would reduce the pollution of this theoretical car for the whole year (City of Los Angeles, 2005). According to the literature, the annual range of particulate matter reduced by green roofs fall between .42 g/m2 and 9.21 g/m2 (Speak et al., 2012; Currie & Bass, 2008; Rowe, 2011; City of Los Angeles, 2005; Yang et al., 2008; Jayasooriya et al., 2017).

Currie and Bass (2008) state that green roofs have the potential to reduce annual amounts of NO_2 by 0.6–2.55 g/m2. Yang et. al (2008) found that if green roofs were built over 198,000 square meters of roofs in Chicago, 452.25 kg of nitrogen dioxide would be removed by green roofs in one year. Rosenfeld, Akbari, Romm, and Pomerantz (2008) calculated that emissions from coal fired power plants to the air could be reduced by 350 tons of NO_x per day in Los Angeles by implementing green roofs. This value of energy saved from the installation of green roofs relates to a 10% reduction in the causes of smog to the city of Los Angeles, with an active NO_x trade program, and results in a savings of one million dollars per day (Akbari, Pomerantz & Taha, 2001; Rosenfeld et al.,1998; Clark, Talbot, Bulkley & Adriaens, 2005) estimate that if 20% of all industrial and commercial roof surfaces in Detroit, MI, were traditional extensive sedum green roofs, over 800,000 kg per year of NO_2 , 0.5% of that area's emissions, can be removed. Yang et. al (2008) states that green roofs annually remove 2.33–3.57 g/m2, NO2 in an urban environment. Jayasooriya et al. (2017) states that green roofs annually remove .37 g/m2 NO_2. In a study done in Singapore, 21% of nitrous acid, a byproduct of nitrogen dioxide, was reduced directly above a green roof (Rowe, 2011). One study implementing green roofs in Kansas City, MO, used by the EPA, estimated that by 2020, green roofs would reduce 1800 pounds (816 kg) of NOx (EPA, 2016). After reviewing the literature, it is found that a green roof can reduce a range of 0.37-3.57 g/m2 (Currie & Bass, 2008; Yang et. al., 2008; Jayasooriya et al., 2017; Rosenfeld et al., 2008) Clark, Adriaens, and Talbot (2008) reported that green roofs yield an annual benefit of \$0.45–\$1.70 per m2 (\$0.04–\$0.16 per square foot) in terms of nitrogen oxide uptake. Clark et al. (2005) estimates that NOx reduction from a 2000 ft2 green roof would provide an annual benefit of $895–$3392, resulting in the green roof being 24.5-40.2% cheaper than a conventional roof without vegetation.

Currie and Bass (2008) state that green roofs have the potential to reduce annual amounts of O_3 by 1.2–3.58 g/m2. Yang et al. (2008) state green roofs have the potential to annually reduce 4.49–7.17 g/m2 O_3 and in their simulation of Chicago, green roofs were built over 198,000 square meters of roofs, the results were measured over the course of just one year, with 871 kg of O_3 removed by green roofs. Jayasooriya et al. (2017) state that green roofs annually remove 1.24 g/m2 O_3 . Since ozone is formed by the reaction of sunlight with pollutants such as nitrogen oxides (NO_x), green house reduction in nitrogen oxides also reduce concentrations of ozone in the urban environment. According to the literature, the annual range of ozone reduced by green roofs fall between 1.2 g/m2 and and 7.17 g/m2 (Currie & Bass, 2008; Yang et. al., 2008; Jayasooriya et al., 2017).

Yang et. al (2008) found that if green roofs were built over 198,000 square meters of roofs in Chicago, 117.25 kg of sulfur dioxide would be removed by green roofs in one year. Currie and Bass (2008) state that green roofs have the potential to reduce annual amounts of SO_2 by 0.2–0.84 g/m2. Yang et al. (2008) state that green roofs annually remove 0.65–1.01 g/m2 SO_2. Jayasooriya et al. (2017) state that green roofs annually remove 0.1 g/m2 SO_2. In a study done in Singapore, 37% of sulfur dioxide was reduced directly above a green roof (Rowe, 2011). One study implementing green roofs in Kansas City, MO, used by the EPA, estimated that by 2020, green roofs would reduce 2600 pounds (1179.34 kg) of SO2 (EPA, 2016). In one field study, the concentrations of acidic gaseous pollutants and particulate matters on a 4000 m^2 roof in Singapore are measured before and after the installation of a green roof. Research found that the levels of SO_2 were reduced by 37% in the air above the roof after installation of the green roof (Yang et al., 2008). After reviewing the literature, it is found that a green roof can reduce a range of 0.10-1.01 g/m2 (Currie & Bass, 2008; Yang et al., 2008; Jayasooriya et al., 2017; Rowe, 2011, EPA, 2016)

As an example of the costs of building a green roof in a U.S. city, the installation costs to install green roofs on every roof in Chicago were estimated to be $35.2 billion (Yang et al., 2008). This brings up a high cost of green roofs that deters many cities from considering installation. The EPA projected in 2009 that extensive green roof installation costs, which were ranging from $15-$20/sq. foot should drop to $8-$15/sq. foot as installations increased, and soil substrate and plants became more available (EPA, 2009). Not everyone considers green roofs for their own homes, however, with the amount of pollution removed and human health improvements and the inherent existent pollution in cities, green roofs are critical to pollution removal in urban environments and should therefore be installed. In fact, having a green roof reduces more pollution in an urban environment than simply not having one at all. Agra, Klein, Vasl, Kadas, and Blaustein (2017) compared green roofs to other roofs of buildings with no vegetation at all (control roofs) and found that the control roofs had a CO2 concentration 50 cm above the ground of almost 375 ppm while the three types of green roofs in the study ranged from maintaining concentrations of 365-370 ppm of CO2 50 centimeters above surface (Figure 1). With green roofs being confirmed to be more effective With costs of green roofs accounted for and their associated improvement of human health via reduction in air pollution, green roofs can become even more desirable with the inclusion of governmental incentives/policies for cost reduction.

Seeing cost as one of the main obstacles standing in the way of green roofs, we urge government action to alleviate this issue. The U.S. government must make green roof installation less expensive through an incentive system. Funding should be granted to all major U.S. cities for the installation of green roofs. Depending on design, plant type, and climate conditions the price of green roof construction typically ranges from $15-20 per square foot, though the EPA projects that extensive green roof installation costs should drop to $8-$15/sq. foot as installations increase, and soil substrate and plants became more available (EPA, 2009). The U.S. Government should offer $10 per square foot of green roof for commercial, residential, and private properties. In target areas where pollution is most concentrated, the government should offer $15 per square foot. This proposal makes the initial up-front cost of green roofs more feasible, if not directly profitable.

Green roofs become more attainable and widespread with the help of government incentives, as shown by successful policies in Washington D.C. Currently, Washington D.C. has over 3 million square feet of green roof (Department of Energy & Environment, 2017a). The district set a goal that by 2020, 20% of its buildings will have green roofs. In 2006, the D.C. Department of Energy and Environment (DOEE) launched the "RiverSmart Rooftops Green Roof Rebate Program" to give grants that encourage the installation of green roofs on private property. The grants offer $10 per square foot and up to $15 per square foot if the building is in target watersheds. With no cap on project size, all properties are eligible including residential buildings. To encourage small buildings to install green roofs as well, the program gives funds to offset costs of structural assessments to buildings of under 2,500 square feet (DOEE, 2017a). This incentive plays a large role in the growth in green roof installation per year in D.C. In 2005, building owners installed 0 square feet of green roof as compared to 104,068 sq feet of green roof installed in 2006, the first year of this initiative (DOEE, 2017b). In 2015, D.C. implemented a whopping 712,493 square feet of green roof. Though there is some variation, there is a general increase in total green roof area in Washington D.C. (DOEE, 2017c). An incentive program similar to this on the federal level would increase the total area of green roofs on a broader scale.

Installing green roofs in urban environments is cost-effective. They reduce the amount of pollution in air, improve the health of people living in urban cities, and can be less expensive to install with the implementation of governmental incentives & policies. If all rooftops in Chicago were covered with intensive green roofs, a projected 2046.89 metric tons of pollutants would be removed (Yang et al., 2008).

When discussing the green roofs ability to improve human health, the concentrations of pollutants most commonly discussed in the literature are O3, SO2, particulate matter, and NO_x (Agra, 2017; Clark et al., 2005, 2008; Rowe, 2011; City of Los Angeles, 2006; Rosenfeld, 1998; EPA, 1998) By installing green roofs, the four main pollutants would decrease in concentration enough to create improvements in human health and economic benefits in the reduction of human mortality. Worker productivity and health is improved along the way, as employees that have a view of nature scenery were less stressed, had lower blood pressure, reported fewer illnesses, and experienced greater job satisfaction (Kaplan et al., 1988; Ulrich, 1984).

The cost-benefit analyses discussed how implementing green roofs would result in savings of a million dollars a day from decreased air conditioning, an overall annual benefit of $895–3392 for each 2000 ft^2 green roof, and a reduction in the particulate emissions of one car for a whole year per square meter of green roof. Green roof financial incentives in Washington D.C. greatly increased the total area of green roofs in the area (DOEE, 2017b). An incentive program paired with indirect incentives would be successful if emulated on a federal level. The U.S. has proven that federal environmental policies can be effective as show by the Clean Air Act (EPA, 2015).

Even though green roofs cost 2-3 times as much as a bare roof to install, government incentives can alleviate these costs to bring installation prices down. With the upfront costs lowered, we can reap the benefits of financial, health, and environmental pay-off by green roofs.

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