Health Impact Assessment of Green Roofs in Ramsey County, MN

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Building Community-University Partnerships for Resilience

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BY

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Abstract

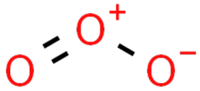
In the United States, 41% of people live in counties with unhealthy levels of ground-level ozone (O_3) or particulate matter. The inhalation of this pollutant causes wheezing, shortness of breath, coughing, and/or a sore or scratchy throat that can be aggravated further by preexisting conditions of asthma, emphysema, and chronic bronchitis. A potential mitigation effort is the application of green infrastructure. There is sufficient evidence that plants can reduce the presence of O_3, including permanently via their metabolic pathways. The annual range of ozone reduced by green roofs falls between 1.2 g/ m^2 and 7.17 g/ m^2. The Surface with a Purpose Project has allocated 449,192,923 potential sq ft in green roofs for Ramsey County Minnesota. This sq ft at various coverage levels was converted to parts per billion (ppb) ozone change to assess the associated health events of asthmatic emergency department visits and hospitalizations and all-cause mortality. While limited practical significance was observed by the scope of this study, the application of these methods to larger and more diverse population sizes along with the addition of other pollutants may give a more holistic picture of avoided negative health outcomes via the conversion of impervious surfaces to green roofs.

Introduction

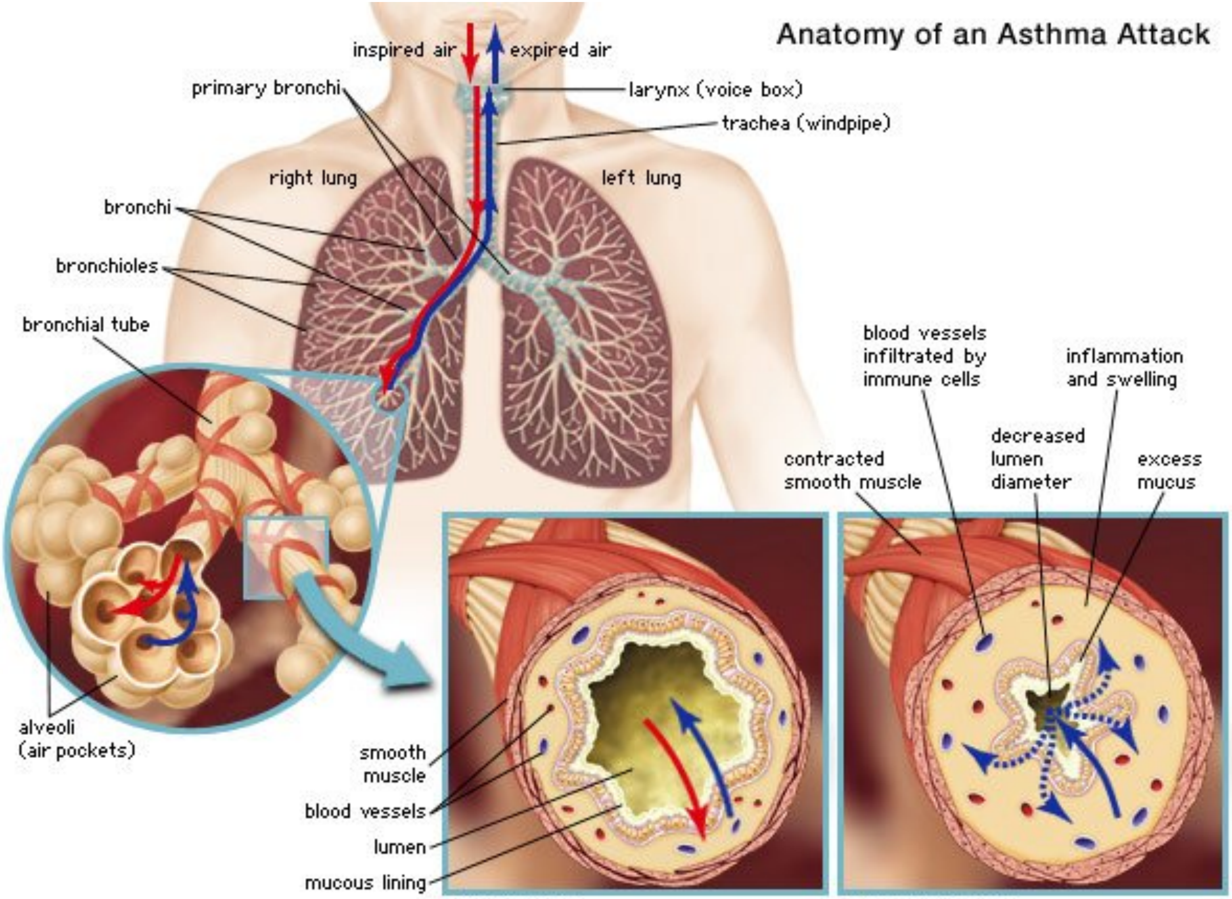
Ozone and Health

In the troposphere, reactions between a nitrogenous base (NO_x) and volatile organic compounds (VOCs) from car exhaust and other emissions and polluting solvents can lead to the formation of ground-level ozone (O_3) given the presence of sunlight (Fares et al., 2010). Once formed, O_3 is a an incredibly unstable molecule, and one of the most powerful oxidizing agents (Streng, 1961).

In the United States, 41% of people in the U.S. live in counties with unhealthy levels of O_3 or particulate matter. Ground-level ozone formation and severity will only increase as climate change continues to cause higher temperatures. This will result in potentially thousands of additional respiratory- related illness and death in the upcoming decades (Rudolph et al., 2018).



When ground-level ozone enters the respiratory tract, it inflames and damages lung tissue. The airway constricts and traps air in the alveoli (air pockets of the lung). This causes an individual to experience wheezing, shortness of breath, coughing, and/or a sore or scratchy throat. Individuals with preexisting conditions of asthma, emphysema, and chronic bronchitis often experience more aggravated symptoms. As a result, related-health events such as asthma attacks increase in frequency (EPA, n.d.).



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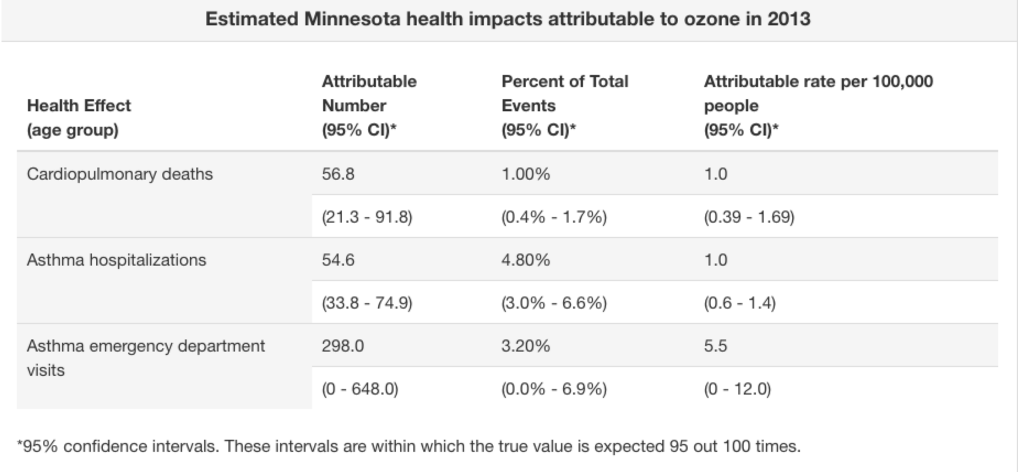
Since ozone can create free-radicals, continued damage of the lungs on the cellular level can occur even after initial symptoms of exposure are gone. This can create conditions like chronic obstructive pulmonary disease (COPD) and leave the lungs more susceptible to infection (EPA, n.d.).

The 2019 *Life and Breath Report* from the Minnesota Department of Health (MDH) reviewed the effects of air pollution based on 2013 population data. The report indicated exposure to fine particles or ground-level ozone was partially responsible for 5-10% of Minnesotans who died, and 1-5% of all Minnesotans who visited the hospital or emergency room for heart and lung problems. These estimates translate to approximately 2,000 to 4,000 deaths, 500 additional hospital stays, and 800 emergency room visits (MDH, 2019).

For ground-level ozone exposure, the summer of 2013 in Minnesota saw the pollutant contribute to an estimated 57 cardiopulmonary deaths, 55 asthma hospitalizations, and approximately 300 asthma-related ED visits (MDH, 2019).

Taken from the 2019 *Life and Breath: How air pollution affects public health in Minnesota*, Table 3



Estimated Minnesota health impacts attributable to ozone in 2013

Health Effect (age group)	Attributable Number (95% CI)*	Percent of Total Events (95% CI)*	Attributable rate per 100,000 people (95% CI)*
Cardiopulmonary deaths	56.8	1.00%	1.0
	(21.3 - 91.8)	(0.4% - 1.7%)	(0.39 - 1.69)
Asthma hospitalizations	54.6	4.80%	1.0
	(33.8 - 74.9)	(3.0% - 6.6%)	(0.6 - 1.4)
Asthma emergency department visits	298.0	3.20%	5.5
	(0 - 648.0)	(0.0% - 6.9%)	(0 - 12.0)

*95% confidence intervals. These intervals are within which the true value is expected 95 out 100 times.

The report also indicated disparities within the Minnesota population; seniors, children, and those with pre-existing heart and lung conditions are impacted by air pollution more than others. Low-income counties and the uninsured were also more disadvantaged by these exposures (MDH, 2019).

Air Pollution and Inequity

Structural inequities of housing environments leave low-income, communities of color, and first-generation immigrant households in areas characteristic to poor air quality. These characteristics include very little green space and proximity to busy roadways and polluting industries (Rudolph et al., 2018).

These inequities stem from U.S. sociopolitical history of institutionalized racism from policies like Racially Restrictive Covenants and The Federal Housing Administration's Redlining practices (Burnside, 2020).

In Minnesota, St. Paul was home to a vibrant and affluent Black community known as the Rondo Neighborhood. In the 1960s, this neighborhood was destroyed by the construction of I-94, displacing 600 of the Rondo Neighborhood's residence (Burnside, 2020). These practices reserved White people the highest quality of residential property and the aftereffects are still present today.

In the U.S., 11.2% of African Americans are currently diagnosed with asthma, compared to 7.7% of Whites. Additionally, emergency department visits for asthma are three times higher in African Americans than Whites. For the U.S. Latinx community, nearly 1 in 2 Latinx live in counties below clean air and ozone standards, and Latinx children are twice as likely to die from asthma as non-Latinx Whites (Rudolph et al., 2018).

When providing solutions, these disparities and history must be acknowledged. Initiatives to address these disparities must match the sociopolitical context and cultural values of the people most affected. The leading principle in all green initiatives should be active participation; the constant, daily multivocality of the affected community in the practices of data gathering, analysis, conclusions, and solutions (Atalay, 2012).

Ground-Level Ozone and Green Infrastructure

There is sufficient evidence that plants can reduce the presence of O_3, including permanently via their metabolic pathways (Fares et al., 2010). Therefore, increased and appropriate plant selection can help mitigate some of the health impacts of air pollution (Gourdji, 2018).

O_3 enters plants through their stomata on their leaves and diffuses into intercellular spaces (Gourdji, 2018). O_3 removal levels are affected by stomatal conductance which maintains a concentration gradient between the internal leaf structure and ambient surroundings (Fares et al., 2010). After entering the stomata, subsequent reactions occur in the intercellular space. If O_3 levels are high it accumulates in this space, decreasing the total O_3 flux (Fares et al., 2010).

However, there are limitations of this reduction of O_3 by plants when non-stomatal uptake takes place due to deposition on plant or soil surfaces (Fares et al., 2010). Too much O_3 can kill a plant if oxidation of the internal leaf occurs by decreasing the plant's carbon uptake (Fares et al., 2010). Secondly, plants emit minimal biogenic volatile organic compounds (BVOCs) that can lead to secondary air pollutant formation under higher stomatal conductance (Alonso et al., 2011).

Yang et al. (2008), assessed the amount of air pollutants that were removed by green roofs in Chicago via a dry deposition model and further assessed the potential of more removal by installation expansions based on different vegetation types. In the paper, the investigators define three types of green roofs: extensive, intensive, and semi-intensive.

Intensive green roofs contain a growing medium with a depth of 15-120cm and can grow larger vegetation of shrubs and small trees. Extensive green roofs' growing medium have a depth of 5-15cm and grow smaller, slow-growing plants. Semi-intensive green roofs have 25% of the growing medium below or over 15 cm but remain less biologically diverse than intensive green roofs (Yang et al., 2008).

Chicago had a total of 19.8 ha of green roofs assessed. 67.42% were intensive or semi-intensive and the remainder were extensive that in total removed 1675 kg of pollutants. O_3 accounted for 52% of the total pollutants removed (Yang et al., 2008).

If all the 27.87 ha of green roofs in Chicago were covered with the same ratio of intensive or semi-intensive and extensive green roofs, 1835.23 metric tons of pollutants could be removed. If all green roofs were extensive by design 1405.5 metric tons of air pollutants would be removed. If all green roofs were intensive green roofs with a 50:50 ratio of tall herbaceous plants to shrubs with small deciduous trees 2046.89 metric tons of air pollutants would be taken up by plants (Yang et al., 2008).

Similarly, in Toronto, air pollution removal was assessed in trees, shrubs, and grass using an Urban Forest Effects Model (UFORE). Once again, intensive green roofs with shrubs removed more air pollution than extensive grass roofs. If baseline shrubs on the ground were supplemented with 20% intensive green roofs, 1.74 metric tons/year of O_3 could be removed (Currie & Bass, 2008).

If baseline trees and shrubs on the ground were supplemented with 20% extensive green roofs, 1.27 metric tons/year of O_3 could be removed. Trees were found to reduce the most air pollutants due to their high surface area (Currie & Bass, 2008).

In a recent 2017 study in Melbourne, Australia Jayasooriya et al. (2017) analyzed air quality improvement via green infrastructure through several different scenarios consisting of trees, green roofs and green walls using i-Tree Eco software. The study found that green roofs had the potential to remove 357 kg/year.

Hypothesis If increasing green roofs in Ramsey County Minnesota reduces ground-level ozone pollution concentrations, then a reduction of air pollution and related human health events should occur when replacing impermeable roofs with green roof surfaces.

Methods

Health impact assessments estimate the change in health endpoint(s) of interest in response to a change in exposure status of a population (Hubbell & Levy, 2009). These assessments, particularly of air quality, share 4 key sources of data from epidemiological literature:

1. Modeled or monitored air quality data
2. Population data (z)
3. Baseline incidence of the health event (y_0)
4. An effect estimate (β)

$$\Delta = yo * \left(e^{\beta * \Delta x} - 1\right)z$$

Δx: Estimating the Change in Ozone measure via Green Roof Systems

In the equation above, Δx is the estimated change in the summary ozone measure (Hubbell et al., 2005). According to the literature reviewed, the annual range of ozone reduced by green roofs falls between 1.2 g/ m^2 and 7.17 g/ m^2 (Currie & Bass, 2008; Yang et. al., 2008; Jayasooriya et al., 2017). The Surface with a Purpose Project has allocated 449,192,923 potential sq ft in green roofs for Ramsey County Minnesota. After converting to m^2 designated percent conversions of this area, these values can then be multiplied by the estimated ozone reduction range by green roofs found within the literature to get the grams of ozone removed per year (g yr^{-1}) **(see Table 1**).

However, major ozone events have seasonality to them, especially for a temperate region like St. Paul, Minnesota. Hubbell et al. (2005) defined an ozone "season," that occurs from 1 May through 30 September, or 153 days. Dividing the value for g yr^{-1} by 153 can account for the ozone events that occur per year to achieve a daily estimated ozone reduction range by green roofs (g/day) **(see Table 1).**

Furthermore, a great deal of the epidemiological literature uses ppb and not dry deposition units as the common unit for ozone. To later be able to correlate change in ozone to a health outcome, conversion to ppb is necessary. Nowak et al. (2006) calculated this percent air quality improvement as grams removed/(grams removed + grams in atmosphere), where grams in atmosphere = measured concentration (g m^{-3}) x boundary layer height (m) x city area (m^2).

To obtain the grams in atmosphere for this study, the ozone monitor closest to the study area of Ramsey County, EPA ID: 27-053-0962 (near I-35/I-94), has estimated ozone levels at 55ppb. The US EPA Reference Standard estimates that 1 ppb= 1.97 ug/m^3 creating a measured concentration of 0.00010835 g m^{-3}. Additionally, the area of Ramsey County is estimated at 390,000,000 m^2 (US Census Bureau, 2013), creating an equation of grams in atmosphere = 0.00010835 (g m^{-3}) x 250 (m) x 390,000,000 (m^2) = 10,564,125 g

Correlating Air Quality Changes with Population Health Outcomes

After establishing green roof sq ft conversion rates with ppb ozone reduction **(see Table 2),** population health outcomes can be applied.

Zheng et al. (2015) completed a meta-analysis of 71 published time series and case-crossover studies for ozone and asthma hospitalizations, estimating a relative risk (RR) of 1.009 $CI_{95\%}$ (1.006–1.011) per 10 ppb increase in ozone for individuals of all ages. Additionally, Di et al. (2017), found that each short-term increase of 10 ppb in warm season ozone (after adjusting for $PM_{2.5}$) resulted in a 0.51% increase in daily mortality $CI_{95\%}$ (1.0041–1.0061). For this health impact assessment, the population size is large enough to assume these RRs approximately equal the odds ratio. The following equation can be applied to convert these relative risks into the correct beta coefficients, where PM= the particle matter in question:

$$\beta = \frac{\text{In}(RR)}{\Delta \text{ PM}}$$

(BenMAP-CE User's Manual Section C-7)

According to Ramsey County Public Health (2018), the asthma hospitalization rate among Ramsey County was 77 per 100,000 residents and the all-cause mortality rate is 677.6 per 100,000. Assuming per Ramsey County Public Health (2018) and the US Census (2019) that the population is about 550,321 people, the avoided ozone-based asthma-related hospitalizations and mortality by each green roof sq ft conversion can be calculated (**see Table 2)**.

$$\Delta = 0.00077 * (e^{0.0008959741 * \Delta x} - 1)550321$$

$$\Delta = 0.006776 * (e^{0.0005087039 * \Delta x} - 1)550321$$

Statistical Analysis

In this study, each effect estimate pulled from the epidemiological literature had an associated 95% confidence interval, creating a factor of uncertainty for the beta coefficient. Monte Carlo simulation substitutes a range of values (the probability distribution) to model all possible results for this factor of uncertainty. It calculates these results multiple times using a different set of random values from the probability functions to establish their potential impact on the evaluation of interest. While these solutions are not exact but estimates, by repeating the simulation numerous times a distribution of the output of interest is established; where estimates of measures of center (i.e., mean) can be ascertained for the parameter of interest. While most Monte Carlo software uses a normal distribution, here a triangular distribution was applied given a lack of standard deviation measurement; where the three parameters of mean value (from the literature's relative risks), minimum and maximum (from the literature's confidence intervals) are used to calculate the most likely value and distribution.

Results

If 100% of green roof coverage is established in Ramsey County, upwards of 0.032 $CI_{95\%}$(0.025-0.037) ozone-related asthmatic hospitalizations and 0.163 $CI_{95\%}$(0.141-0.184) all-cause mortalities can be avoided. If 75% of green roof coverage is established, 0.020 $CI_{95\%}$(0.025-0.029) ozone-related asthmatic hospitalizations and 0.126 $CI_{95\%}$(0.110-0.144) all-cause mortalities can be avoided.

If 50% of green roof coverage is established in Ramsey County, upwards of 0.017 $CI_{95\%}$(0.013-0.020) ozone-related asthmatic hospitalizations and 0.088 $CI_{95\%}$(0.077-0.099) all-cause mortalities can be avoided. If 25% of green roof coverage is established, 0.009 $CI_{95\%}$(0.007- 0.011) ozone-related asthmatic hospitalizations and 0.047 $CI_{95\%}$(0.040-0.052) all-cause mortalities can be avoided.

Discussion

In translating the practical significance of this study, it is important to recognize its scope of one air pollutant in one county of Minnesota. The ramifications of this make the health findings appear less impactful. If applied to a larger area, for instance Chicago metro, where the population is about 16 times that of Ramsey County, a far greater affected population and therefore impacted population would receive the beneficial health factors of green roofs. Also, given the inequity of asthma and housing, more diverse areas with higher baseline incidences would benefit a great deal more. If more air pollutants were considered, potentially larger effect estimates could show greater avoided hospitalization and all-cause mortality, especially when combined with ground-level ozone.

Additionally, achieving these health outcomes per change in ozone (ppb) per sq ft of green roof required a great deal of assumptions, including but not limited to; independent observations, a clearly defined ozone season, uninformative removal at each green roof location, uninformative criteria for an asthmatic hospitalization for Ramsey County residents, extrapolation from ground-layer concentration to total pollution within the boundary layer (assuming a well-mixed boundary layer), and a discrete area of interest for green roofs and their impact. In addition, the population of Ramsey county was viewed as large enough to assume that the relative risks approximate the odds ratio in order to calculate the effects estimate.

Furthermore, unmeasured impacts are found within the precursors of ground-level and plant physiology. Since ozone formation requires warm temperatures evapotranspiration and shade provided by plants can decrease air temperatures thus minimizing the production of some air pollutants like O_3 in the first place (Gourdji, 2018). Ozone also requires a nitrogenous base (NO_x), where reduction in nitrogen oxides also reduces concentrations of ozone in the urban environment.

Like O_3, NO_2 is also absorbed via the stomata and can react with water inside the leaf structure to form nitric as well as nitrous acids that can undergo other reactions with other compounds present in the plants. Plants which contain more elevated leaf ascorbate concentrations can remove more NO_2 air pollution (Jim & Chen, 2008).

In Guangzhau, China, NO_2 removal was assessed based on monthly air pollutant measurements, land use, and tree coverage. Areas with high tree coverage reduced the most air pollutants, but variation occurred in species tolerance of NO_2 (Jim & Chen, 2008). Highly NO_2 tolerant trees included Curtain Fig, Camphor, Chinese Ash, Chinese Arborvitae, Aavin Juniper and Australian Laural. Moderately tolerant trees included Ailanthus, Southern Magnolia, Eastern Nettle and Blackboard Trees (Jim & Chen, 2008).

Plant selection by O_3 also matters. In the spring and summer, deciduous trees are responsible for up to 90% of O_3 removal, likely because they emit minimal biogenic volatile organic compounds (BVOCs) that can lead to secondary air pollutant formation under higher stomatal conductance (Alonso et al., 2011). Drought tolerance is also crucial: drought stress in the summer months tends to decrease stomatal conductance, lowering O_3 deposition. However, in colder less drought-prone climates, stomatal conductance is highest in the summer and the greatest rates of O_3 removal occur. Winter and fall see the lowest level of O_3 due to lack of deposition by deciduous broad-leaf species (Alonso et al., 2011). Furthermore, pollen-production of the plant can inflame respiratory conditions like asthma; negating the desired positive health impacts and making low-pollen count a crucial component to plant selection as well.

Based Gourdji (2018)'s Review of plants to mitigate various pollutants in Montreal, Drought-tolerant, deciduous, broad-leaf plant species that minimize structural load and can tolerate Canadian climate (much like Minnesota's climate) are Japanese Maples (*Acer palmatum*) 'Shaina' (1.75 m) and 'Mikawa-Yatsubusa'(1.5m). Japanese maples can withstand Montreal winters, are sun tolerant, and can cope with minimal watering once established. The NO_2 -tolerant specie that minimizes structural load and can tolerate Canadian climate, while minimizing BVOC was the *Magnolia 'Genie'* (3-3.5 m) (Gourdji, 2018).

Conclusion

Based on the literature, to see the most health impacts I believe the intensive system, particularly with deciduous tree/shrub species would be the most impactful system for the Twin Cities. Given the health impact assessment, plant physiology and therefore plant selection impact the value ground-level ozone change. Those better suited to conditions mentioned in the discussion would likely see the higher ranges of ozone change found in this study.

While limited practical significance was observed by the scope of this study, the application of these methods to larger and more diverse populations sizes along with the addition of other pollutants may give a more holistic picture of avoided negative health outcomes via the conversion of impervious surfaces to green roofs.

Tables/Figures

Table 1. Green Roof Sq ft to ppb Ozone Change

Green Roof Coverage (sq ft)	m^2	g yr^{-1}	g/day	Daily % Air Quality Improvement	ppb Ozone Change
100% = 449192923	41731370.13	50077644.15-299213923.8	327304.86-1955646.56	0.0300516-0.15620465	0.0165-0.0859
75% = 336894692.3	31298527.59	37558233.11-224410442.8	245478.65-1466734.92	0.02270931-0.12191439	0.0125-0.067
50% = 224596461.5	20865685.06	25038822.08-149606961.9	163652.43-977823.28	0.01525502-0.08471908	0.0084-0.0466
25% = 112298230.8	10432842.53	12519411.04-74803480.9	81826.22-488911.64	0.00768614-0.04423324	0.0042-0.0243

[a] 1 sq ft= 0.092903 m^2

[b] Annual range of ozone reduced by green roofs falls between 1.2 g/ m^2 and 7.17 g/ m^2 (Currie & Bass, 2008; Yang et. al., 2008; Jayasooriya et al., 2017)

[c] 1 year = approx.153 days of ozone events

[d] Daily % Air Quality Improvement = grams removed/ (grams removed + grams in atmosphere) (Nowak et al., 2006)

[e] ppb ozone change= Daily % Air Quality Improvement multiplied by ozone monitor EPA ID: 27-053-0962

Green Roof Coverage (%)	Ozone Change Based on Literature	Ppb Ozone Change (Δx)	Incidence Rate (y_o)	Effects Estimate (β)*	Population Size (z)	Avoided Hospitalizations (CI$_{95\%}$)	Avoided Mortalities (CI$_{95\%}$)
100%	Min	0.0165	0.00077	0.0008959741	550321	0.006 (0.005-0.007)	
100%	Max	0.0859	0.00077	0.0008959741	550321	0.032 (0.025-0.037)	
100%	Min	0.0165	0.006776	0.0005087039	550321		0.031 (0.027-0.035)
100%	Max	0.0859	0.006776	0.0005087039	550321		0.163 (0.141-0.184)
75%	Min	0.0125	0.00077	0.0008959741	550321	0.005 (0.004-0.005)	
75%	Max	0.067	0.00077	0.0008959741	550321	0.020 (0.025-0.029)	
75%	Min	0.0125	0.006776	0.0005087039	550321		0.024 (0.021-0.027)
75%	Max	0.067	0.006776	0.0005087039	550321		0.126 (0.110-0.144)
50%	Min	0.0084	0.00077	0.0008959741	550321	0.003	

						(0.002-0.004)	
50%	Max	0.0466	0.00077	0.0008959741	550321	0.017 (0.013-0.020)	
50%	Min	0.0084	0.006776	0.0005087039	550321		0.016 (0.014-0.018)
50%	Max	0.0466	0.006776	0.0005087039	550321		0.088 (0.077-0.099)
25%	Min	0.0042	0.00077	0.0008959741	550321	0.001 (0.001-0.002)	
25%	Max	0.0243	0.00077	0.0008959741	550321	0.009 (0.007- 0.011)	
25%	Min	0.0042	0.006776	0.0005087039	550321		0.008 (0.007-0.009)
25%	Max	0.0243	0.006776	0.0005087039	550321		0.047 (0.040-0.052)

Table 2. ppb Ozone Reduction & Associated Changes in Health Outcomes

* $\beta = \frac{In(RR)}{\Delta PM}$ Where RR= the relative risk from epi literature and Δ PM= 10 accounting for the 10-unit change in ozone for both effect estimates.

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