ESTIMATES OF AIR POLLUTION MITIGATION WITH GREEN ROOFS USING THE UFORE MODEL

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Abstract

The purpose of this study was to investigate the effect of green roofs on air pollution in urban Toronto. The researchers looked for synergistic effects in air pollution mitigation by manipulating quantities and species of trees and shrubs at grade level and grass on roofs within the study area. The effect of these vegetation manipulations were simulated using the Urban Forest Effects (UFORE) computer model developed by the USDA Forest Service Northeastern Regional Station, Syracuse, New York. Originally UFORE was developed to help forestry managers and researchers quantify urban forest structure and risks based on standard field, meteorological and pollution data. While UFORE contains four different assessment modules A - D, Module D quantifies the effect of vegetation on air contaminants such as NO_2, SO_2, CO, PM_{10} and ozone. UFORE also provides data about hourly air contaminant removal rates and it predicts an economic externality value in USD for total air contaminant removal. Six vegetation scenarios were developed within the Toronto study area to compare how different amounts of vegetation affect air contaminant levels. Results of the study indicate that grass on roofs (green roofs) could play a significant role in air pollution mitigation in an urban neighbourhood. By extension, a 10-20% increase in the surface area dedicated to green roofs on downtown Toronto buildings would improve air quality and quality of life for citizens in Toronto.

ACKNOWLEDGEMENTS

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CHAPTER 1: INTRODUCTION AND STUDY INFORMATION

Introduction

Use of vegetation on walls and roofs of buildings, particularly roofs, is a common practice in the architecture of older buildings in countries like Iceland, Scandinavia, Switzerland, Germany and Tanzania. Historically, people in these countries utilized vegetation in the form of vines on walls, shade trees near buildings and grass on roofs, hitherto known as green roofs, to provide: wind protection; shade from hot summer temperatures; insulation for winter warmth and summer cooling; as well as to enhance the aesthetic value of the building. Canadian prairie pioneers constructed buildings with sod bricks for use in wall and roof construction where the soil and plants acted as a protective structure and insulation material in both summer and winter months. In the 1970s an interest in studying the environmental benefits provided by vegetative elements applied to buildings prompted researchers to examine the effects of green roofs on building performance. Throughout Europe, particularly Germany, the last thirty years have produced a compliment of academic green roof research, predictable research funding and a proliferation of green roof installations. These accumulated study results have helped to formalize European municipal policy guidelines, regulations and financial incentives that today, support a thriving European green roof economy. After nearly thirty years of this mostly German science, knowledge and expertise in green roof construction technologies in Germany is unsurpassed in the western world (29, 86, 87, 90).

As green roofs and research have proliferated throughout Germany and Europe, so too have the improvements in green roof technology in response to increased market demand. Europe and, more recently, North America boast a complement of green roof expertise including green roof consultants, plant specialists, adapted green roof irrigation systems, electronic roof leak detection systems, green roof drainage technologies, root barrier technologies, synthetic planting media technologies and horticultural practices (80, 85, 86, 87, 90). It is estimated that while over 10 million square meters of green roof have been

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installed in Germany over the past two decades, this represents only 14% of the total flat roof surface available (39). While North American green roof installations lag behind our European counterparts, so to does the availability of peer-reviewed publications that support and quantify the regional differences and similarities among the purported myriad of environmental benefits associated with green roofs. Studies across North America tend to be university-based technical and construction-based research studies that concentrate on: stormwater runoff quantity and quality; thermal energy and roof membranes; urban heat island effects; plant and substrate compositions; policy reports; and social/recreational benefits associated with green roofs.

Study Background

There is currently very little scholarly North American research available to quantify the environmental benefits associated with green roofs. Literature supporting these benefits tends to be scattered, brief and mostly available in proceedings from two recent international green roof conferences – one in Chicago, Illinois, (2003) and one in Portland, Oregon, (2004). To date, this literature has focused mostly on case studies of demonstration projects across several North American cities. Other research has examined the role of different substrate depths, substrate types, degree of plant coverage and the effect of slope on stormwater runoff quantity and quality. Ottawa-based research at the National Research Council has explored how green roofs contribute insulation value to buildings, especially in summer months. Of note is the dearth of evidence in the existing literature to support the air pollution benefits associated with adding vegetation to roof surfaces in urban areas (6, 9, 17, 29, 87). Studies that quantify air pollution benefits might play an important role in guiding the formation of urban green roof policy especially if green roofs can be shown to improve air quality and by extension the quality of life in urban areas.

Study Hypothesis

The thesis hypothesis was that the UFORE (Urban Forest Effects) Computer Model could quantify the mitigation effect of green roofs (vegetation layer, that is grass, installed on conventional roofs) on levels of air pollutants or contaminants in a study area within City of Toronto. The UFORE Model was chosen because of its accepted use within the scientific community of urban and regional foresters throughout North America. The UFORE computer model uses measured field data inputs as well as local hourly meteorological data and air pollutant concentration measurements (collected from Environment Canada, 1998) to quantify neighbourhood-specific vegetation effects on urban air pollutant concentrations (76).

As a result, the study objectives were to estimate:

- Air pollution benefits derived from different subsets of trees, shrubs and grass on roofs
- If a quantified surface area of green roof coverage could be recommended to inform urban policy
- If the UFORE Computer Model provides a systematic and consistent method for determining the air pollution benefits derived from green roofs in urban neighbourhoods

Study Assumptions

The principal research questions imbedded in the study were as follows:

1. Can the UFORE Computer Model generate air pollution outputs from a smaller neighbourhood study area of green roofs within the City of Toronto?

2. Will these UFORE Model air pollution outputs facilitate green roof design (size or surface area) parameters for the City of Toronto?

To answer these questions there were a number of assumptions that needed to be held:

1. That UFORE Module D could respond to the grass-on-roof (green roof) vegetation inputs that did not fit the typical input data provided by field-derived tree and shrub species parameters within the study area.

2. That UFORE Module D could respond to the addition of green roof vegetation inputs on surface areas of neighbourhood roofs and be interpreted in the same manner as adding tree and shrub inputs at grade level.

3. That UFORE MODULE D could distinguish differences between vegetation scenarios and their effects on individual air contaminant levels.

As such, the research focused on the resultant individual air contaminants derived from UFORE Module D that showed incremental changes associated with the manipulation of vegetation types within the study neighbourhood.

CHAPTER 2: BACKGROUND

What is a Green Roof?

For the purposes of this study, green roofs will refer to those conventional flat or sloped roofs that have been amended with some or all of the following layers or elements: structural support, vapour control, thermal insulation, a water proofing membrane, a roof drainage layer, a root-protection layer, synthetic planting media and hardy, drought-resistant plants. These green roof layers (see Figure 1) can be adjusted or enhanced based on the needs of the designer or building owner.

Figure 1: Green Roof Layers

Plant Layer

Vegetation Layer

Drainage Layer

Protection Layer
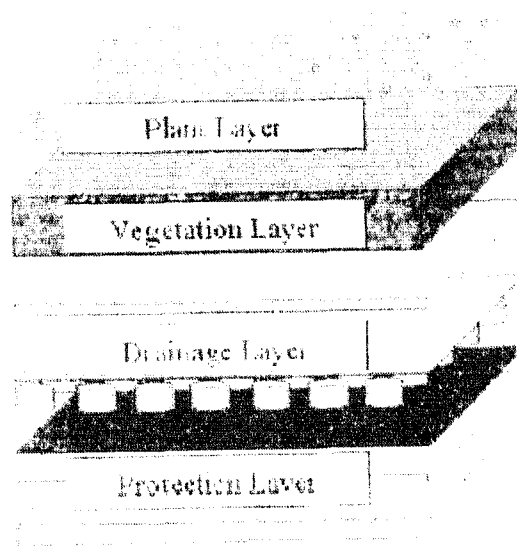
(Martin Tand & Drainage, 2005 p.1)

Green Roof Terminology

There are two main green roof terms: the extensive and the intensive green roof. These terms are used to delineate, describe and compare the differences in construction, design and costs associated with green roofs. An extensive green roof is the most typical green roof utilized in the world today. It has a substrate depth ranging between 5-15 cm and weighs between 72.6 – 169.4 kg per meter

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squared (87). A shallow soil or a soil-less synthetic planting medium is required on most roofs to decrease loading weights and meet acceptable building code and structural demands. These low-weight synthetic planting media combined with challenging microclimate conditions associated with prevalent wind, drought and high temperatures present on an elevated surface, necessitate plant species choices that are hardy, low in height, and drought-resistant. According to many authors, minimal technical expertise or practical experience is required to install and maintain an extensive green roof; however, the success of any roof is measured by the survivability of the plants therein. Ongoing plant and substrate research is contributing to green roof success across North America (11, 31, 38, 39, 43, 46, 81, 85, 93, 101, 111, 120).

Their heavier weights, deeper planting media, irrigation systems, landscaping planning and design and complex roof engineering characterize intensive green roofs. In contrast to extensive green roofs, intensive roofs are eligible for a much broader plant species selection (including trees and shrubs), as well as other design features such as ponds and decorative landscaping formations. Intensive green roofs require costly roof structural upgrades and necessitate higher overall maintenance costs as they are often installed by an experienced landscaper and require heavy equipment including overhead cranes to convey materials up to the roof.

Table 1 delineates the major characteristics that differentiate extensive green roofs from intensive green roofs. Of particular note are the differences in weight, cost, structural preparation, water retention, predicted thermal benefit and public versus private benefits.

Table 1: A Profile of Extensive and Intensive Green Roofs

Roof Type	Extensive Green Roof	Intensive Green Roof
Cost	▪ 10 – 14 $ per square foot	▪ 14 – 35 $ per square foot (unlimited)
Growing media and plant selection	▪ 5 -15 cm planting media ▪ little or no irrigation ▪ stressful conditions for plants – require low, drought-resistant species	▪ 15 - 50 cm planting media ▪ irrigation system required ▪ favourable for many varieties of plants e.g. trees, shrubs and perennials
Structural preparation	▪ light weight: (roof generally does not require structural strengthening) ▪ suitable to cover large surface areas	▪ heavier in weight and requires structural engineering ▪ used over smaller surface areas in landscaped containers
Insulation value (energy savings)	▪ 5% insulation added value for building savings (summer cooling)	▪ similar insulation value (summer cooling) if covers same surface area
Stormwater	▪ 5-10% peak flow reduced in 5-10 cm planting depth	▪ not well-studied or compared on intensive roofs
Air pollution	▪ mitigates air contaminants	▪ mitigates more air contaminants (better if evergreen trees and shrubs used versus deciduous trees/shrubs or grass and meadow species)

Urban heat island	• contributes to a reduction in daytime temperatures over roof area • improves local oxygen supply	• contributes to greater reduction in daytime temperature as trees and shrubs provide more active evapotranspiration • improves oxygenation
Biodiversity	• Simulates lost grade-level habitat for many species of invertebrates. (fewer avian species, although has not been well-researched)	• Allows for greater diversity of plant species and provides habitat for birds (Black Redstarts, starlings, chickadees and sparrows to name but a few) • beetles spiders and other invertebrates • Simulates lost habitat for wildlife, birds and heritage seeds from grade level
Public Access	• suitable for public access on roofs with 0-30 degree slopes as long as parapet walls meet building code	• suitable for public access, more aesthetically-positive as roof can be used for meeting recreational need (Singapore, 2003) and for food production
Advantages	• low maintenance • can survive without irrigation and drainage systems • relatively little technical expertise needed to install • suitable for retrofit roof	• deeper planting media supports, more biodiversity, more overall environmental benefits and more social/psychological benefits by accessing recreational roof space

	projects	
	▪ vegetation can spontaneously colonize	
	▪ less expensive	
	▪ aesthetically natural in appearance	
	▪ easier for municipalities to enforce	
Disadvantages	▪ Limitation on plant species choices ▪ limited access for the public ▪ can be less aesthetically pleasing, especially in winter time	▪ heavier loading on the roof ▪ more costly due to higher requirements for water, energy maintenance, and irrigation supplies ▪ more costly to structurally prepare roof loading ▪ more costly for expertise to design and install green roof

(Peck et al., 1999)

CHAPTER 3: LITERATURE REVIEW

Green Roof Research in North America

As we approach the first decade of scientific exploration, green roof research is slowly becoming more established in North America. Green roof research has been guided by interdisciplinary scientists wishing to establish, compare and analyze the performance of green roofs on environmental parameters in North American climate zones, using North American plants, across varying regions and contexts. For example, the findings of urban stormwater runoff quantity and quality studies can differ between Vancouver, British Columbia and Toronto, Ontario, based on plant species, substrate choices, slope, rainfall patterns and green roof construction materials. Similarly, urban heat island, air pollution mitigation, roof membrane longevity, heat flux, insulation capacity, plant types, soil depths, biodiversity and species conservation can differ by province, region and climatic zone across North America. As yet, there is no common baseline for comparisons within the North American context.

Green roof research is notably dispersed across a wide range of researchers including: soil and horticultural scientists, civil and construction engineers, architectural scientists, landscape designers, climate change meteorologists, air pollution experts, ecologists, roofing specialists, urban planners and policy developers. North American research, while relatively new compared to Europe, is informing green roof installations, policy development and implementation as well as achieving measurable penetration in the marketplace. Market expansion is especially observable in cities like Chicago, Illinois, Portland Oregon, Washington, D.C., New York City, Atlanta, Georgia, Vancouver, British Columbia and Toronto (10, 16, 37, 42, 43, 46, 51, 70). Comparatively, European countries have lead the world in green roof research as a response to urban sprawl, polluted stormwater runoff, lost green space, air pollution, urban heat island effects and species at risk. Consequently, Europe has more mature and tested green roof municipal regulations and financial incentives to promote the installation of green roofs.

Barriers to Canadian Market Development

One of the barriers to widespread adoption of green roof technology in Canada is the lack of technical data on green roof performance and longevity within the Canadian context. In the absence of technical data, it is difficult for developers, lenders, roofing contractors and building owners to acquire education and awareness, and those who do receive it, are hesitant to adopt the technology. Moreover, the additional 'up front' cost (see Table 1, chapter 1) associated with installing a green roof compared to a conventional roof is a real financial barrier that has yet to be removed. Nonetheless, ongoing contributions by technical and scientific green roof research facilities, with carefully instrumented green roofs for data collection and comparison, coupled with an academic commitment for knowledge transfer, are expected to build baseline data across North America. Canada has three established research facilities, while the remainder are located in the United States (8, 10, 43, 58).

Green Roof Policy; Europe and North America

In European countries such as Switzerland, Austria and Germany, developers are less concerned by the perceived added costs associated with the installation of green roofs (13, 14). It seems that Europeans are guided by a longer-term vision for the performance and longevity of built form compared to that of North Americans. In Europe, buildings are designed to last approximately 50-100 years, compared to the 20-25 year projections currently used in North America (13). In Switzerland, the building code necessitates that new developments possess a cement roof. Cement is a building material that can be reclaimed and recycled from other buildings that require demolition. Cement not only strengthens the building and adds to its longevity, but also makes the roof ideal for the additional loading requirements of an intensive green roof. In Basel, Switzerland, the building code necessitates the incorporation of a green roof that protects and sustains the biodiversity of native invertebrate species. The Basel, Switzerland building regulation specifies that a developer must incorporate a green roof, and consult with Dr. Stephan Brenneisan, a scholar in the design and study of biodiversity on Swiss green roofs, in all new building projects in the

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city (13, 14). Other environmental pressures, such as a lack of available urban space for development, air/water pollution and an over-reliance on drinking water sources that have traversed several countries and their waste water treatment plants before reaching the down stream water purification facility, have motivated European governments to adopt mitigation strategies such as green roof technology and sustainable building design.

Some European governments have amended their building codes and developed regulations while others have used financial incentives to encourage builders and developers to consider green roof technology. For example, the Split Waste Water Act (SWWA) in Germany allows municipalities to change the tax structure levied to building owners based on the amount of stormwater runoff generated by a particular property (103). In these countries, a stormwater fee is calculated by the percentage of a building's total impervious surface area comprised by parking lots and rooftops, compared to that of its total footprint area. Hence, the addition of a green roof decreases a building's impervious surface area and curbs the costs associated with the SWWA (88, 103). This policy direction places a share of the responsibility for abating water pollution in the form of stormwater runoff directly on the building owner.

Throughout North America, a system called Leadership in Energy and Environmental Design (LEED™) is helping to raise the profile of sustainable building practices more common in Europe (49). LEED™ is a USA-based, non-governmental rating system for developers that is administered by the National Green Building Council. LEED™ criteria have been established to ensure that building projects meet a variety of environmental design goals, such as water and energy conservation, in-door air quality, reduced urban heat island impacts, reduced impact on wildlife and many other criteria. Throughout North America, municipalities like the City of Portland, Oregon and the City of Chicago, Illinois have begun to promote LEED™ certification on their public buildings. Green roofs are a recognized mechanism to attain credits on the LEED™ rating scale

(28). Some authors suggest that LEED™ certified buildings have a stronger marketing edge over others in a similar market (88). Other incentives that fostered green roof policy development in the City of Chicago include the Energy Conservation Code. This ordinance was passed in 2001 and made all new and retrofit roofs meet a minimum standard for solar reflectance (48). The ordinance was shaped in response to a severe heat wave (1996) in Chicago that contributed to a significant number of deaths, particularly in senior citizens. Green roofs became an accepted form of low reflectivity and helped to mitigate urban heat island effect and thereby improve Chicago's air quality (48). In addition, Chicago grants a density bonus option to developers in the form of a floor area premium. To qualify for more intense development or more floors, a minimum of 50% of the roof surface area or a minimum of 2000 square feet (whichever is greater) must be covered by vegetation (38).

According to some authors, the City of Portland, Oregon, leads North America in supportive green roof policy (113). In 2001, Portland's Bureau of Environmental Services and the Office of Sustainability combined forces and created financial incentives to encourage green roof research on local demonstration projects. Currently, the City of Portland offers technical assistance, access to accumulated research data and access to grant monies to further the development and installation of green roof demonstration projects. Similarly, the City of Portland's City Public Works Code 17.38 now requires that stormwater runoff be managed at source. Green roofs, or eco-roofs as they are called in Portland, meet water quality and peak flow control requirements of this new code (51). Finally, Portland's Floor Area Ratio (FAR) Bonus allows green roofs or eco-roofs to support an application to develop more space. For example, if an eco-roof is projected to cover up to 30% of the roof surface area, one square foot of bonus space is allowed for each square foot of eco-roof. Moreover, where an eco-roof is expected to cover greater than 60% of the roof surface, each square foot of eco-roof generates three square feet of density bonus (51).

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Policy development in Canada lags behind that of Europe and the United States. The cities of Vancouver, Toronto and Ottawa have green roof research facilities integrated at the academic level with demonstration projects that are contributing to a greater understanding of the environmental benefits offered by green roofs. In 2003 the Greater Vancouver Regional District (GVRD) completed a GIS-based inventory of green roofs and was purported to be the first database of its kind in North America (22). The GVRD has established a working group where municipal, provincial and federal levels of government will coordinate green roof research and provide a forum for exchanging technical data on green roof performance, explore policy options and promote green roofs in the Vancouver Region. In October 2004, the British Columbia Institute of Technology (BCIT) opened its green roof research facility to 1,200 square feet of research roof area. Green roof data from BCIT will be shared with researchers in Ontario, in particular, the Toronto Region Conservation Authority-based consortium and the Ottawa-based National Research Council, Institute for Research in Construction, Field Research Facility (53). Toronto's green roof demonstration projects, a first for Canada, are located at Eastview Community Centre and on the podium roof at Toronto's City Hall. Environmental benefits are being quantified via extensive instrumentation within the roof membranes and growing media on green roofs in Toronto and Ottawa.

Policy incentives that directly impact the development and installation of green roofs are currently lacking in Canada. According to some authors, the use of direct or indirect public incentives for green roofs is preferable over more traditional regulatory approaches, as evidenced in Chicago. Regulatory approaches shift the burden of additional capital costs associated with green roofs directly on to the building owner or developer – while direct or indirect incentives may stimulate the market using traditional municipality-based funding mechanisms. A large number of criteria influence the choice of design and implementation of a particular policy instrument. Factors such as how quickly the instrument needs to be implemented, how expensive the instrument will be for

tax payers and building owners, as well as the overall cost consideration for the municipality will influence the outcome, especially if enforcement, inspection or monitoring is part of the implementation strategy (34). The challenge for any Canadian jurisdiction will be to determine which green roof policy instruments (government grants, subsidies, low interest loans, or tax expenditure) will promote local industry.

In the next sections of the literature review, a summary of research reports that quantify the environmental benefits associated with green roofs will be profiled.

Stormwater Management

Impervious urban surfaces contribute to the diversion of stormwater or runoff rainwater away from land into engineered municipal systems. Impervious dark surfaces also contribute to the solar gain and subsequent urban heat island effect noted in urban areas throughout the world (2, 3, 8, 14, 15, 23, 27, 28, 33, 54, 58). According to studies by the Toronto and Region Conservation Authority, approximately 25% of urban land development area in new subdivisions in Ontario replaces native or green natural habitat with impervious surfaces (58). Similarly, according to a study by the City of Portland, Bureau of Environmental Services, American cities are comprised of as much as 30-90% impervious surfaces. Impervious surfaces include rooftops and other asphalt surfaces (51).

Impervious surfaces create problems for municipalities, human and natural communities in urban areas for the following reasons:

- In a rain event, stormwater runoff becomes contaminated with pesticides, oil, grease, heavy metals, rubber, and garbage from roads, driveways, parking lots and roofs as it hits surfaces, accumulates and travels toward engineered urban storm drains. Polluted water journeys untreated and unchecked toward local rivers, wetlands, lakes and other bodies of water (20).

- Combined sewage overflows (CSOs) and sanitary sewage overflows (SSOs) occur when stormwater systems (combined sewer and storm systems) reach maximum capacity and overflow during heavy rainfall or in a typical spring runoff. In Toronto, diluted raw sewage may be discharged into local streams and rivers that feed contaminated water to Lake Ontario with a resulting host of negative environmental and human health impacts (20, 58).

- A steady drop in local water tables (related to the lack of infiltration from urban impervious surfaces) has been affected by the engineered storm water redirection into viaducts, underground concrete conduits, and stormwater outflows, which terminate in major bodies of water (104, 106).

- Stormwater runoff increases shoreline water temperatures, particularly during summer months and impacts the habitat for aquatic plants, fish and animals and encourages algae blooms along stormwater outlets.

- Shoreline erosion results as the speed, turbidity and volume of engineered stormwater runoff follows a storm event (20, 58, 110, 106).

Research on the stormwater benefits attributed to green roofs is being conducted at several facilities across the United States and Canada. According to North American Wetland Engineering, Pennsylvania, one of the most tangible benefits of green roofs is their ability to retain stormwater runoff during the first hour of a storm event and thereby reduce the amount of runoff water reaching combined sewer networks (17, 60). The City of Toronto incurred over 22 CSOs during the summer of 2004 and incurred financial penalties not only from the Ministry of the Environment but from lost revenues that accompany beach closures related to Public Health advisories (20). Municipalities are particularly concerned about the first 1-2.5 cms of stormwater runoff, referred to as the first flush. According to some research, this initial runoff water carries the most concentrated pollutants from impervious surfaces (28).

Green roofs are estimated to absorb, filter, retain and store an average of about 50-75% of the precipitation that falls on them, especially during the first hour of a rainfall event. The water retention capacity of a green roof varies according to the type of growing media used – that is, if the growing media include a lightweight, water-retaining aggregate in the matrix – its water-retaining ability will be higher than those that do not. Growing media comprise an area of current study at green roof research facilities, where competing companies are involved in comparative studies that examine water retention, volume, load, quality of stormwater runoff and plant nutrition capability between product groups. Many stormwater studies indicate that a layer of planting medium 6-8 cms deep in an extensive green roof can absorb about up to 2.5 cms of water, or in some cases up to 50% of the water that falls in a rain event (28, 51, 58, 70, 96).

United States Stormwater Regulations and Green Roof Development

The United States passed Phase II Final Rule of the National Pollutant Discharge Elimination System (NPDES) in 2001 and intensified the requirements for stormwater permits by emphasizing the importance of stormwater Best Management Practices or BMPs. BMPs such as bio-retention areas, wet and dry detention ponds, swales, constructed wetlands and sand filters are now commonly utilized throughout Canada and North America (51, 20). The Phase II Rule challenged developers and planners in dense urban areas like Raleigh, North Carolina to think about how green roofs could contribute to stormwater management and stimulated the need to support green roof research at the University of North Carolina (UNC). At UNC, researchers compared green roof retention and runoff rates, differing soil depths and sloped roofs to conventional urban roof performance. Findings from South Carolina support Canadian research by Liu and McMillan where green roofs significantly reduced first flush peak flow runoff rates and retained on average about 50% more rainwater than conventional roofs (53, 58). Research by Thompson demonstrated that green roofs can retain up to 60-100% of the stormwater they receive especially when soils are dry and unsaturated before a rainfall event (107). Many researchers

concur that green roofs perform best at retaining rainwater when there has been adequate time for evaporation to occur between storm events (107, 70, 58, 110, 104, 96).

Interestingly, researchers have reported that stormwater runoff quality may be hindered by green roofs. Two reports note that green roof runoff leachage levels tested for nitrogen and phosphorous were higher in green roof stormwater runoff data compared to conventional roof data (51, 70). This complements work by MacMillan who reported that runoff water quality parameters such as nitrogen, phosphorous, e-coli, heavy metals and copper were higher from the green roof runoff at York University, Toronto, compared to the reference roof. Findings like these have researchers and regulatory bodies responding to synthetic media supply companies for more stringent testing and research on leachate runoff quality over time before bringing products to market (58).

Rowe's (2003) investigations at the Centre for Green Roof Research compared green roof parameters against conventional roofs by varying types of growing media including PEPP (porous expanded poly propylene), using different planting media, varying depths, slopes and testing these differences against several varieties of Sedum. These data were compared to pre-existing German studies by Liesecke (41), who noted that differences in rainwater retention were commensurate with depths of plant media, such that more robust plant communities on green roofs contributed to a greater ability to retain stormwater. Rowe (2003) has demonstrated that in over 24 rain events, the Sedum green roof retained over twice the amount of rainwater as the conventional gravel ballast roof. The conventional roof had a 75% runoff rate, whereas green roofs resulted in 37% and 34% runoff rates, respectively. This translates to 63% and 66% retention rates.

Schade (2000) reported that the quantity of roof runoff obtained from a thin (2-3 cm) layer of extensive green roof at slopes of 1, 2, 10, 20, and 30 degrees was commensurate with the slope of the roof. This finding was supported by Rowe

(2003) such that a more sloped roof provides a greater quantity of roof runoff in a shorter period of time. Overall, leading stormwater researchers concurred that green roofs retained between 50- 60% of their stormwater (51, 53, 54, 96, 98, 70) and that in all cases, the more rainfall, the greater the amount of runoff that was rendered from all roofs. However, in addition to reducing the total volume of runoff, vegetated roofs also reduced the peak runoff rate and delayed the total runoff volumes (51, 53, 107).

Canadian Stormwater Research
Ottawa
Ottawa-based research completed by Liu and Baskeran provided a groundbreaking report on the effect of green roofs on stormwater runoff. As such, their research is well cited across construction and engineering-based stormwater literature and provides a benchmark for comparisons of green roof performance (28, 58, 70, 96). Results shown in Figure 1 are profiled for stormwater runoff from six inches of planting media (see performance for runoff 'G') compared to a conventional or reference roof (runoff R) at the National Research Council, Institute for Research in Construction, Field Research Facility green roof site in October, 2001. It was revealed that after a light rain event (34 mm) over 15 hours in October 2001 the green roof provided a significant delay in the start time for rainwater runoff and reduced the rate and volume of runoff available.

Table 2: Cumulative rainfall and runoff rates Ottawa site
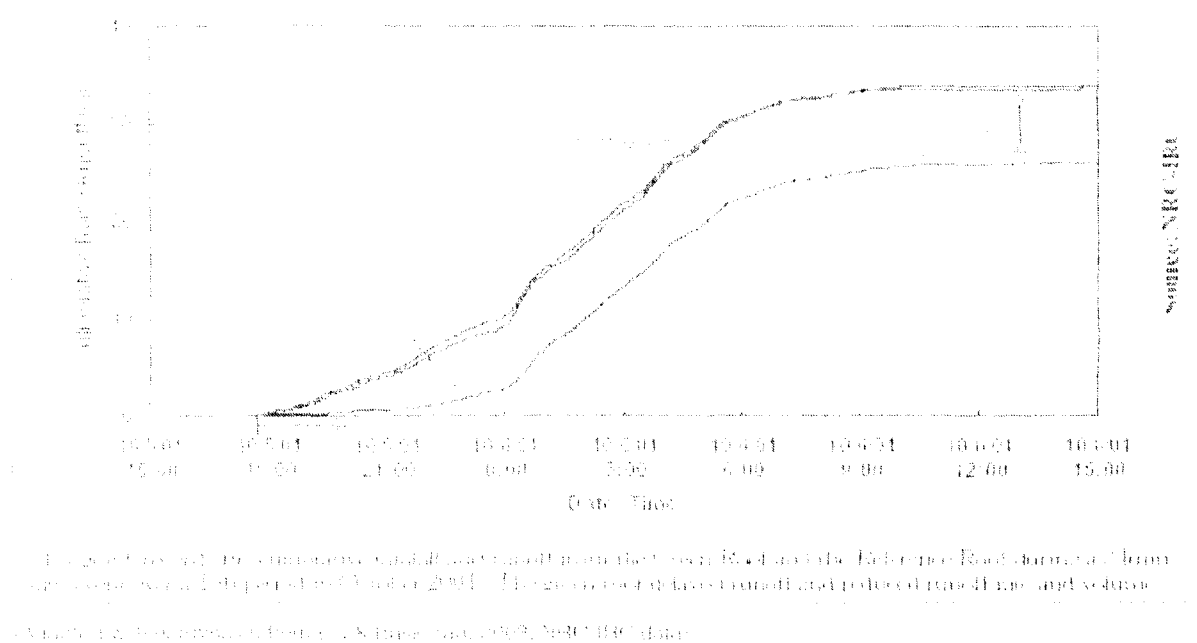
By comparing the rainfall and runoffs from the green roof and the reference roof, it is obvious that the green roof affected stormwater runoff in three ways:

1. Green roof delayed runoff by 35 minutes from the start of the event.

2. Green roof reduced runoff rate - initial runoff was 1.8 mm/h while runoff from the green roof was reduced to 0.8mm/h. This reduction diminished as the growing medium or substrate was saturated.

3. Green roof runoff volume - demonstrated that a minimum of 8 mm out of the 38 mm of rain was retained in the green roof system. This was felt to be a conservative number as the growing medium was not dry to begin with (53, 54)

Toronto

In November 2003 two extensive green roof research sites were established in Toronto, Ontario, one at the computer science building at York University and the other on a retrofit roof at the Eastview Community Centre, 86 Blake Street, Toronto. Research is funded by Toronto and Region Conservation Authority, the City of Toronto, a Federal Green Roof Systems Consortium and Green Roofs for

Healthy Cities, a non-profit clearinghouse in Toronto (58). This research is also supported by the National Research Council, Government of Canada and particularly by, Karen Liu, the principal NRC construction investigator. The York University and Eastview Centre extensive green roofs are instrumented and connected via a web-based monitoring system (hardware and software) with real-time monitoring of all climate and hydrometric parameters. The system collects signals from sensors and stores and publishes them through the website. The green roof research site at York University is approximately 500 meters square (5000 sq. ft). It has two test plots, one with vegetation and one as the control where each plot is approximately 100 meters square. Specific vegetation and substrate characterizations as well as irrigation and storm runoff storage tanks have been installed as part of the study. The slope of the roof garden is approximately 10%. The ability to quantify stormwater data in Toronto is a principal research aim of the York University facility, as results from this site will inform decision makers at the Toronto Regional Conservation Authority and City of Toronto watershed management offices (58).

Vancouver

A modeling study in the Greater Vancouver Region (GVR) demonstrated that green roofs can protect streams and reduce flooding risk in mountainous urban regions. Researchers there developed a scenario-modeling tool, the Water Balance Model (WBM)™ in order to evaluate the performance of green roofs (28). Their modeling efforts show that green roofs are potentially very effective at reducing the volumes and peak rates of runoff from heavily developed areas in the GRV, especially in the southern parts where rainfall is typically lower. Vancouver-based research reports that even thin extensive green roofs were effective at reducing peak runoff rates during short high-intensity storms such as summer 'cloudbursts'. An inventory of Vancouver's green roofs revealed that there are many more extensive than intensive green roofs (19). Thicker intensive green roofs were found to be more effective at mitigating runoff from prolonged winter Vancouver storms (28). These researchers predict, based on modeling

results from a 50-year watershed retrofit scenario, that re-development of existing buildings with green roofs could: counteract increased rainfall (amount and severity) associated with global climate change, mitigate flood risk, improve water quality and prevent further degradation of fish habitat. This is especially relevant as urban planners are working with the assumption that the GVE population could double in the next 50 years (33).

Vancouver stormwater research reveals that:

1. runoff volumes decrease with increased soil depth but tend to diminish after about 10 cm, especially for higher rainfall locations (figure 2 and 3).

2. about 25-30 cm of soil depth is needed to stabilize runoff rates from large prolonged winter storms that typically occur in the region (figure 2).

3. significant reductions in runoff rates result from short intense storms (ie. cloud bursts) that occur in dry weather periods in (10 cm) of soil depth (figure 3).
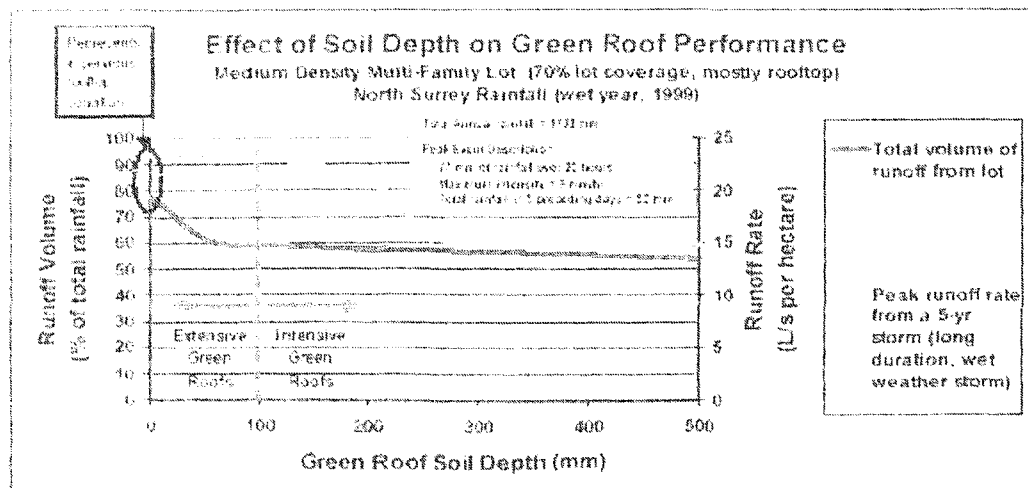
Figure 2: Effect of Green Roof Soil Depth on Performance During Wet Weather

(Graham (2003) Water Balance Model (WBM)™)

According to this research, green roofs provide more significant reductions in runoff volumes when total annual rainfall depths are lower in average (figure 4 below). The runoff volumes achieved by green roofs appear to be directly related

to the amount of evapo-transpiration that has occurred from the rooftop plants. Their modeling illustrates that as the total annual rainfall decreases, potential evapo-transpiration becomes more significant relative to total rainfall. These researchers suggested that green roofs would be most effective in drier parts of the GVR (White Rock or Delta) in drier years as opposed to wetter years.
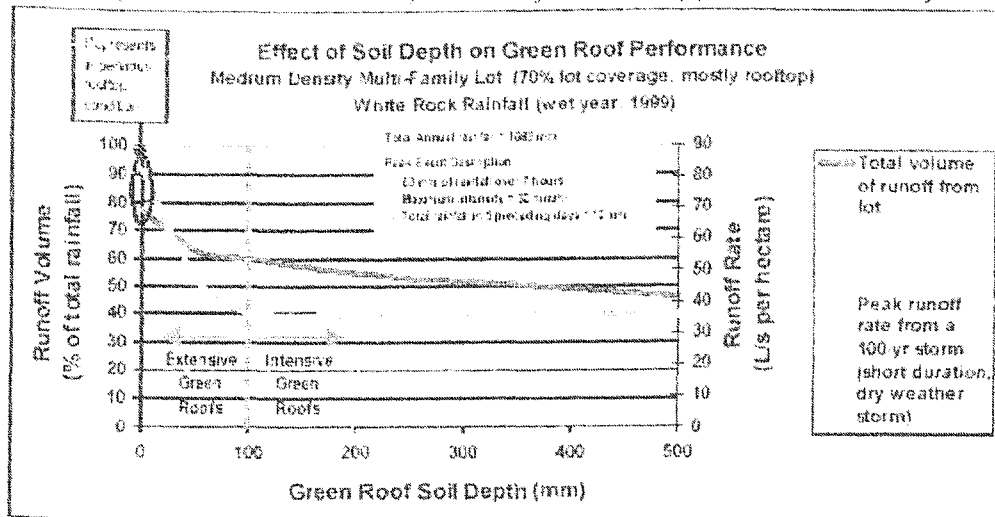
Figure 3: Effect of Green Roof Soil Depth on Performance During Drier Weather with High Intensity Cloudbursts

(Graham (2003) Water Balance Model (WBM)™)
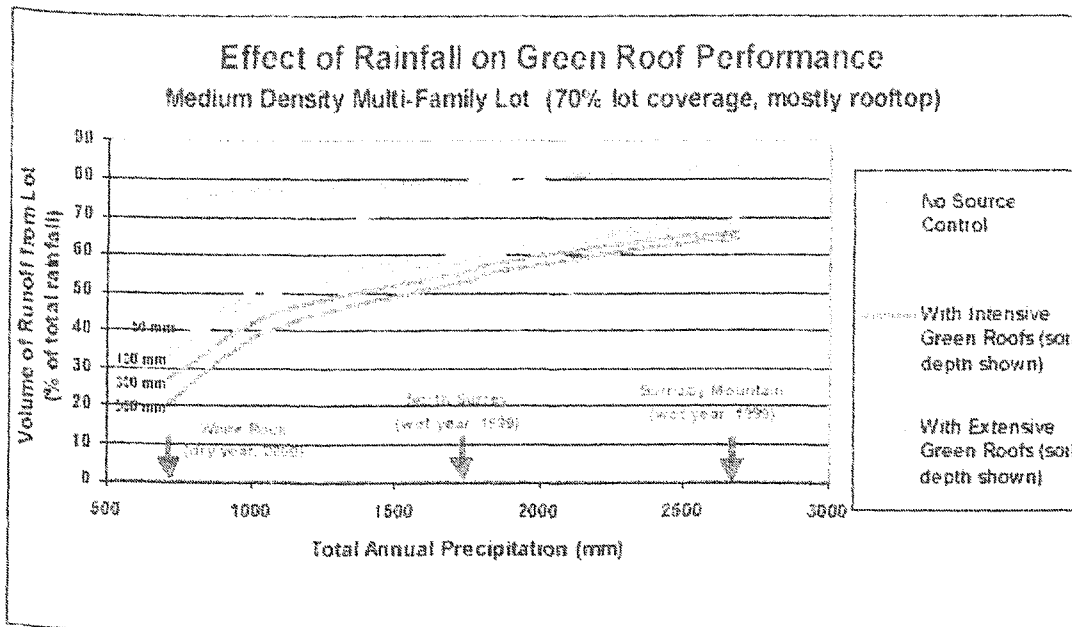
Figure 4: Effect of Total Rainfall on the Volume Reduction Benefits of Green Roofs

(Graham (2003) Water Balance Model (WBM)™)

Graham suggested that the green roof-related reductions in volume and rate of runoff are probably most significant when planned for dense urban areas, such as those with a higher ratio of roof top coverage to ground level impervious areas, such as high-density multi-family or commercial buildings without substantial parking lot surfaces (33).

Urban Heat Island Effect
Urban heat island (UHI) is a phenomenon that results when green vegetated land areas are replaced by non-porous surfaces typically found in cities (26). Urban heat islands occur when the summer sun's ultraviolet rays are absorbed by dark, impervious urban surfaces and radiated back into the air as heat energy. Hence, many cities in the USA and Canada generate downtown air temperatures that are as much as 5.6 degrees Celsius warmer than their surrounding rural areas (8). When trees and vegetation are removed from a city, the natural cooling effects of shading and evaporation of water from soil and leaves (evapo-transpiration) is lost. As previously stated in the section on stormwater management, plants provide a source of moisture through evapo-transpiration, or the movement of water back into the atmosphere as water vapour. Urban heat islands are created when solar energy is trapped in non-porous surfaces and released as heat throughout the day.

> "Greater partitioning of absorbed solar energy into evapo-transpiration reduces the amount of energy stored in urban materials and released as heat, thereby reducing the temperature of the vegetated surface and the low-level air" (8, p. 45).

Tall buildings and narrow street corridors can trap hot air that further reduces and restricts natural airflow. In addition, waste heat energy from cars, trucks, factories, cooling towers and air conditioners adds more heat to the urban air and contributes to urban heat island effect (3, 6).

Typically, heat islands are influenced by a city's proximity to water and the direction of the prevailing wind conditions. In Toronto, offshore winds and rain

can 'flush out' hot air from the city center and reduce the heat island effect. On the other hand, sunny windless days can exacerbate the heat island effect, as hot polluted air is trapped in the urban core of Toronto (6, 7, 3, 4). Higher temperatures associated with the heat island effect act to threaten public health, as noted by several speakers at the Toronto Urban Heat Island Summit (8). Chiotti reported that there are specific health risks associated with living in the urban heat island effect such as stresses associated with high summer temperature, poor summer air quality and exposure to UV radiation. These stresses were reflected in increased morbidity, increased hospital admissions and increased death rates related to exacerbations in respiratory and cardiac conditions. While heat-related mortality is difficult to measure Chiotti estimated that the total death rate from hot summer temperatures in Toronto ranged from 9.63 - 33.65 per 100,000 population during summer heat waves (17).

Currently, the literature reveals little primary research on the effect of green roofs on urban heat island effect beyond a significant reporst by Bass, Akbari and Konopacki (2, 3, 8). Bass cites other authors, who compare temperatures between various urban surfaces. For example, summer temperatures on urban paved roads ranged between 45 and 60 °C compared with surface temperatures in forests, wooded areas and grasslands that fell below 30 °C. While intuitively this work and others would support a vigorous urban tree planting policy to reduce urban heat island effect, Bass posits that green roofs are a more realistic urban planning tool for reducing surface temperatures. One reason is that urban roof surfaces are plentiful and, in many cases, unimpeded by overheard wires, streets, sidewalks or paved surface areas (8). Data collected from conventional gravel and tar roofs suggest day time temperatures can reach between 60-80°C; hence, when one adds up the thousands of square feet of conventional roof coverage in Toronto, it can be argued that conventional roofs are exacerbating the urban heat island effect and the vertical movement of suspended particulates, dust and pollutants into the local atmosphere within the city (3, 9, 18, 23).

According to Bass urban heat island exists in different layers, one of them being the urban boundary layer (8). This is a layer extending roughly from the rooftop level up to the level where the urban influence is no longer felt. Temperatures in the boundary layer can impact temperatures at canopy level, that is, the level where most people live. The temperature and chemistry in the boundary layer drives the several chemical reactions that create ozone and further degrade air quality levels. It is speculated that summer temperatures on rooftops at high elevations can affect the chemistry occurring in the boundary layer.

Conventional rooftops are often hotter than surrounding grade level temperatures (3, 6, 8). This finding not only exacerbates the urban heat island effect but also serves to heat up the top floors of tall buildings, homes and office structures. In turn, higher temperatures in buildings cause discomfort to tenants or occupants, especially on the uppermost floors. These warm temperatures exacerbate a reliance on fossil fuels to power air conditioning units that make conditions more tolerable inside buildings. Concomitantly, warm temperatures cause an increase in the electricity demand for refrigerators that struggle to maintain cool temperatures in tall, hot buildings. Overall, building energy demand increases due to the added solar thermal load that is transferred through a conventional roof into the uppermost floors of a building (95). As such, rooftop heat loading and increases electricity demand from local coal-fired generating plants with a resultant increase in emission of air pollutants including, greenhouse gases, nitrous oxides and particulates (8, 3, 53, 54). Conversely, reviews by Wong et al. and Kohler et al. have shown that indoor temperatures under a green roof system are at least 3-4°C lower than outside temperatures of 25 to 30°C (47, 115).

In order to accurately model Toronto's urban heat island, Bass (2001) utilized a mesoscale meteorological model called the Mesoscale Compressible Community Model (MC2) (6). Bass reported that the during testing, the model revealed a

weak urban heat island in Toronto, and this had implications for the overall green roof effect on surrounding air temperatures. Toronto's green roof coverage was modeled as 5% of total land use and was spread evenly over the city. Bass was able to examine commercial and residential high-density areas in Toronto and add irrigation to their green roofs by modeling the effect of irrigation at ground level. When irrigation was added to 5% of the green roofs, the temperatures were reduced by at least 2°C over the green roof areas. Studies on thermal movement of air have shown that there is less vertical air movement over grassy surfaces (106). According to the work of Minke and Witter grassy surfaces do not heat up to more than 25°C. This is mostly due to the fact that with evapotranspiration there are large amounts of solar radiation converted into latent heat which prevents the temperature from rising (67, 106).

Urban Heat Island and New York City

The New York City Ecological Study (NYCES,) started in New York City in 2003, appears to be one of the most sophisticated studies of the green roof effect in North America. Currently, Phase 1 involves the completion of a cost-benefit analysis of green roof development (1). Other green roof components of the study include an analysis of: urban heat island; energy and regional warming; hydrology; health impacts; building and urban infrastructure; and policy. The urban heat island research is conducted by Dr. Cynthia Rosenzweig of the NASA Goddard Institute for Space Studies, Dr. William Solecki of Montclaire State University and Dr. Stuart Gaffin of the Columbia Earth Institute. This team plans to document the existence of the New York City urban heat island by comparing meteorological station data in urban and suburban regions of the New York metropolitan region. They plan to present their multi-year findings at the International Greening Sustainable Cities conference in Washington 2005 (30).

These researchers have developed a regional climate model that has been used to test the role of green roofs as "cooling engines" and "runoff traps" for the region as a whole. Using local New York City scenarios, they plan to conduct an

analysis of how temperature, urban heat island, cloud cover and wind speed might change over the region in response to global warming; results may provide further justification for green roofs as a useful urban adaptation strategy. Finally, these researchers plan to make linkages between green roofs and temperature reduction, air quality and energy benefits apparent by modeling scenarios that demonstrate simple green roof results can be aggregated to form neighbourhoods that will help to estimate long-term changes to the city's temperature, air quality and building energy consumption rates (16).

Building Roof Membrane Performance

The Ottawa-based National Research Council, Institute for Research in Construction, Field Roof Facility work collaboratively with the North American Roofing Industry, in support of green roof research on building performance. These researchers have examined building energy parameters and roof membrane protection studies. Liu suggests that green roofs not only protect roofing membranes from damaging weather and heat conditions, but most notably, green roofs reduce membrane exposure to intense ultraviolet (UV) radiation (54). In effect, vegetation on green roofs serves to moderate temperatures along the roof membrane so that daily fluctuations in temperature are less damaging to the structural matrix or integrity of the roof membrane. Similarly, green roofs shade and protect the roofing membrane from extreme fluctuations in temperature that follow the hottest summer days and the frigid temperatures in winter conditions. According to Liu and other authors, temperature fluctuations lead to the micro and macroscopic contractions and expansions within the membrane layers, which promote cracking and premature aging of the membrane (54, 99, 80, 95). The lifespan of conventional roofing membranes is predicted to be 20 years (19, 21, 27, 60, 62). Some authors accept that green roofs extend the lifespan of the roofing membrane to an estimated 40 years (28). According to European researchers Liesecke and Johnson a London (UK) department store installed a green roof in 1939 and 50 years later the membrane was inspected and found to be in excellent condition

(50, 43) From this single report, it appears that green roof membranes out-performed others in a climate where membranes have a lifespan of about 10-15 years. If further research supports this finding, a longer lifespan for roofing membranes provides a two-fold economic advantage in that it extends the life of the membrane and decreases the burden on landfill sites. Both of these attributes represent a cost savings for the building owner and the environment.

Building Energy and Heat Flux

There are several energy flux' terms that require consideration within a green roof energy balance system. The figure on the following page illustrates the seven main terms: (i) shortwave radiation incoming; (ii) shortwave radiation reflected; (iii) longwave radiation incoming; (iv) longwave radiation emitted upwards; (v) sensible heat loss or gain; (vi) latent heat loss; and (vii) heat conduction downwards or upwards from the room below the roof. Equations for most of these flux terms are available from standard atmospheric science and heat transfer studies and are not to be considered in this report (30).

## Figure 5: Basic roof energy balance
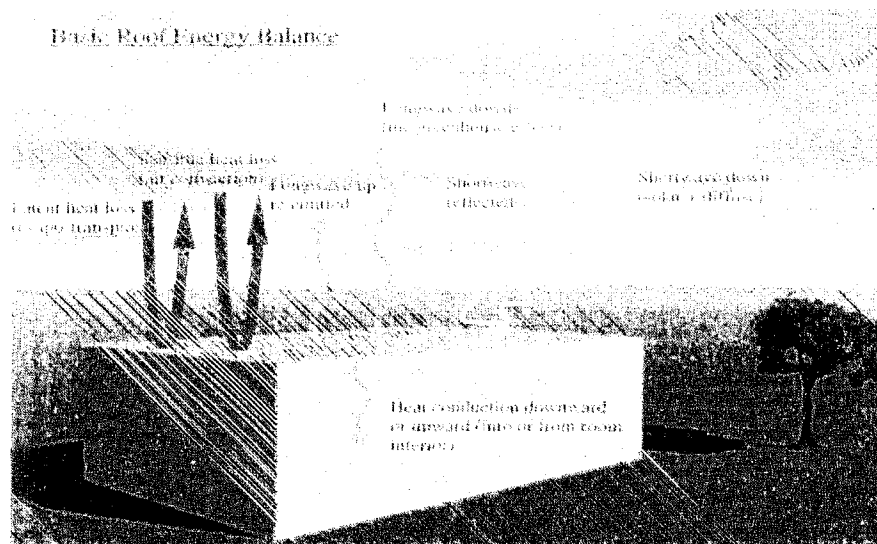
(Gaffin 2005) Seven energy fluxes' considered in the green roof energy balance model.

'Flux' means energy passing through a unit area per unit time, such as 'Watts / meter per hour' or 'BTU / foot per hour'.

Liu's research on building energy is supported by others who report that green roofs reduce building energy demand especially peak demand during high summer temperatures (3, 95, 97, 119). Ultimately, decreased energy demand reduces greenhouse gas emissions associated with coal-fired electricity generation. Researchers suggest that green roofs not only provide direct shading over the roof membrane and improve the insulation or R-values of the roof membrane, but also reduce air temperatures surrounding the roof of the building as plants evapo-transpirate and absorb short-wave solar energy (53).

At the Ottawa research site, a green roof supported with 6 inches of growing medium reduced the surface temperatures of the roof membrane significantly in summer months. In summer, reference or conventional roof membrane temperatures were 70 C compared to the green roof membrane which rarely topped 30 C. Liu's research also demonstrates how a green roof modulates daily surface temperature fluctuations along the roof membrane to within 6°C. The green roof then moderates heat flow or heat gain that passes through the roof into the upper floors of the building and influences daily building energy demand for air conditioning. Liu's report showed significant reductions in total heat flow when comparing the green roof and the reference roof. This translates to a reduction of over 75% in building energy demand as per Table 3 (54).

Table 3: Thermal comparisons between reference and green roof. Ottawa site

	Reference Roof	Green Roof	Reduction
Heat Gain	19.3 kWh/m^2	0.9 kWh/m^2	95%
Heat Loss	44.1 kWh/m^2	32.8 kWh/m^2	26%
Total Heat Flow	63.4 kWh/m^2	33.7 kWh/m^2	47%

Heat fluctuations between roof membranes in the figures on the following pages illustrate that there are notable temperature differences between the conventional or reference roof and the green roof. A significant thermal benefit is provided by the green roof and fewer kilowatts of energy are required to maintain indoor temperatures at a steady state. The next three figures are adapted from Lui and Baskeran's research at the Ottawa research facility and show comparisons in heat gain and heat transfer between the green roof and the reference roof. The figures also illustrate the differences in thermal benefit between a green roof and a reference roof (54).
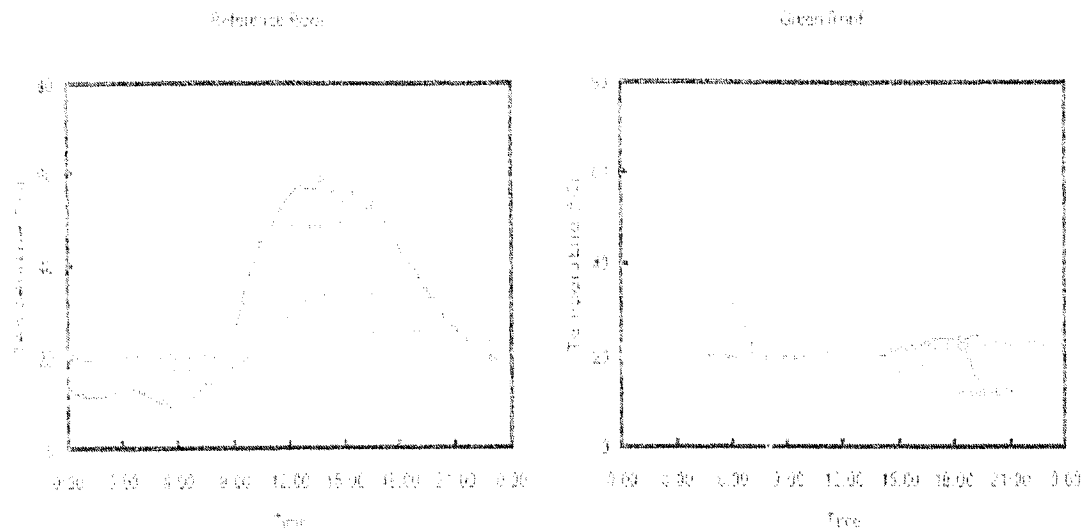
Figure 6. Temperature profile within the roofing systems on a summer day (July 16, 2001) indicating that the Green Roof reduces the temperature fluctuations within the roofing system (54).
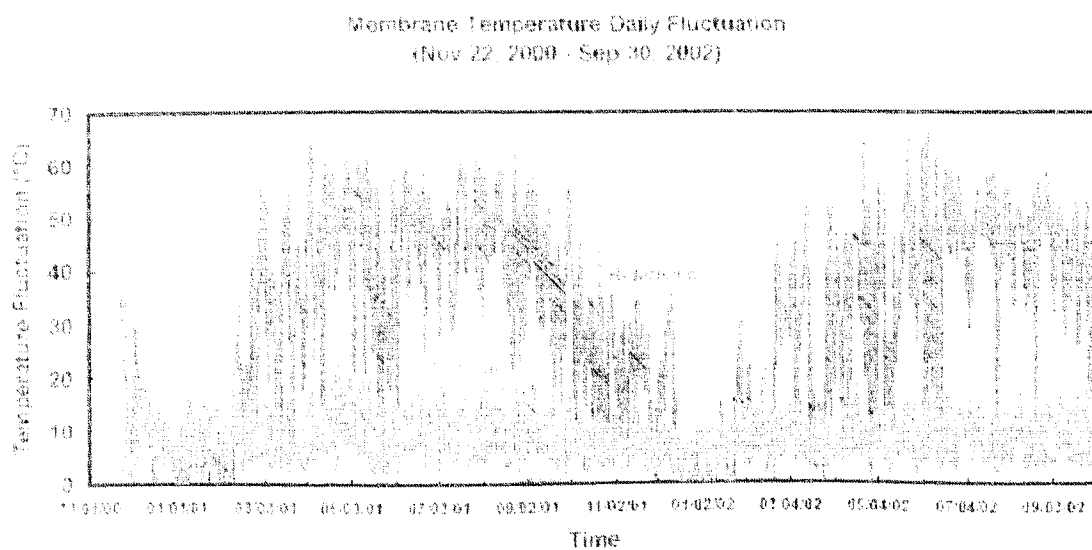

Figure 7. Temperature measurements showed that the Green Roof significantly reduced the daily temperature fluctuations experienced by the roofing membrane. (54)
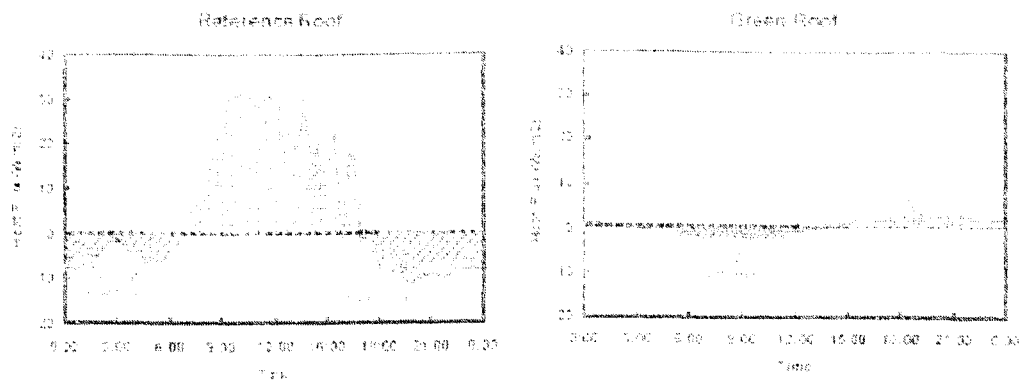
Figure 8: Heat flow through the roofing systems on a summer day (July 18, 2001) indicated that the Green Roof reduced the heat flow through the roofing system significantly. (54)

These Ottawa studies are supported by a consortium of researchers at the National University of Singapore's Centre for Total Building Performance and the National Parks Board of Singapore (109, 110). The Singapore team's results strengthen previous findings that heat gain through the roof under the green roof was significantly reduced compared to an exposed reference roof. In Singapore, exposed paved roof portions peaked at 57°C with diurnal fluctuations up to 30°C. In contrast the temperatures under the foliage of various low palm species peaked at 27°C with a maximum diurnal fluctuation of 3°C. The vegetated rooftop also reduced ambient air temperature, the mean radiant temperature and the temperature of reflected radiation to the ambient environment. This study supports other evidence that rooftop gardens can mitigate the urban heat island effect that may be more accentuated in a tropical climate (30, 97).

A study by Siaz and Bass (2005) described how the ESP-r model (Environmental Systems Performance – research) illustrated the effects of green roofs on building energy demand in a multi-storey residence in Madrid, Spain in summer and winter conditions. The annual energy consumption was calculated for this residence according to three different scenarios: a basic flat roof (FR), a green roof (GR), and a Aljibe roof (AR). Aljibe refers to Spanish green roof technology

with the capacity for water storage that can be ___ed for watering the green roof or for grey water collection or fire protection.

Table 4: Comparison between the total annual energy consumed for heating and cooling

	FR Flat Roof	GR Green Roof	% Reduction	AR (Aljibe Roof)	% Reduction
Heating (KWh)	240,620	240,344	.12	240,184	.2
Cooling (KWh)	90,233	84,639	6.2	84,545	6.4
Total KWh	331,053	325,183	1.8	324,729	1.9

Table 4: Adapted from Saiz and Bass (2005) Annual energy consumption in 3 scenarios

The reductions in energy consumption are due to the combined effect of lower thermal conductance and lower solar radiation absorbed in the green roof (GR). Even though the energy savings can be considered small (less than 2%), it is noteworthy that the building's roof area was only 16% of the total building envelope (97).

Onmura et al. conducted field measurements on a series of planted roofs in Japan (82). They reported that an evaporative cooling effect created by the rooftop lawn garden showed a 50% reduction in heat flux into the rooms below the garden. Their research reported a reduction in surface temperature from 60° C to 30°C during the day and helped to strengthen the role played by healthy plants and evapo-transpiration in reducing the building heat flux.

Peak Energy Values
Saiz and Bass (2005) examined the effect of green roof systems on a building's peak energy consumption in summer, in Madrid, Spain. The resultant total energy consumption for the peak days dropped by 12% under the green roof systems compared to a common flat roof. Two types of green roof systems – a typical green roof (GR) and an Aljibe roof (AR) – had different conductance values (10% lower in the AR) but the difference in energy consumption between these cases was almost negligible (1% lower in the building with the AR). These

results show the reduced effect of differences in the thermal roof conductance values on the overall thermal performance of the building and highlight the significant role of green roof vegetation in absorbing solar radiation, especially during peak energy consumption.

Saiz and Bass calculated peak energy consumption for each zone in a multi-residential building to evaluate the effect of the green roof on building energy consumption within floors of the building (figure 9) (97). They reported that energy flow is not uniformly distributed in buildings and that the reductions in peak energy consumption throughout a building vary from floor to floor. The largest reduction in cooling energy consumption of 25% was achieved in the floor directly under the green roof. From there, the cooling effect progressively decreased from the top floors down to the basement of the building.

Figure 9: Summer cooling reductions achieved within multi-story building
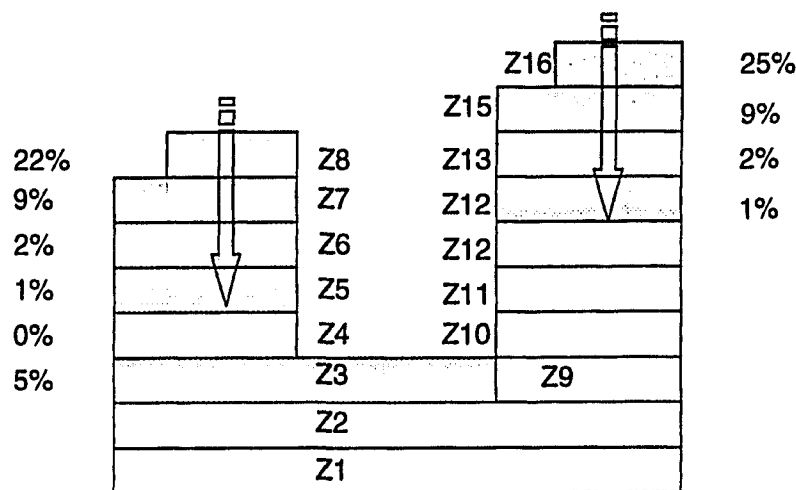
(Figure 9: Adapted from Siaz and Bass (2005). Peak summer cooling energy reductions achieved within the 8 storeys of the study building. A green roof is located over zone 8 and zone 16)

Building energy savings are predicted to arise from green roof vegetation in the following ways: it absorbs solar radiation; it shades the roof membrane; it increases the thermal resistance of the membrane; and it provides a cooling effect by releasing moisture in evapo-transpiration. Of note in this study, a green

roof added to merely 16% of the building roof surface resulted in a total annual energy consumption reduction of 1% in the heating season and a 6% reduction in the cooling season. However in the upper floors, a significant energy reduction of 25% was noted during the peak summer demand and 12% during the winter (97).

Habitat Restoration and Conservation

A dictionary definition for habitat suggests that it is a specific surrounding within which an organism, species or community lives. It includes physical elements (temperature, humidity, moisture and light) biological factors (species diversity, breeding partners) and the presence of food and predators (59, 93, 43). As urban development encroaches on surrounding habitats like rivers, wetlands, forests, meadows and grasslands, these habitats can be extirpated or destroyed. Loss of habitat threatens species evolution, differentiation and survival of native plants, animals and insects. Green roofs provide an elevated vegetated platform that may in time serve as an adapted urban habitat for some of the displaced native plants, animals and insects.

Green roofs as habitats are being studied in Europe (13, 32, 31). Green roofs have been found to be stepping-stone habitats that can connect natural isolated pockets of biodiversity to one other. This is particularly valuable when isolated communities within a green roof can communicate with each other overland using bridges provided by logs or sticks. Green roofs can also be reached by air pathways that can be used by migrating birds, nesting birds, insects and air-borne seeds. Researchers suggest that green roofs serve as connecting habitats as part of a larger system of wildlife corridors that protect species within urban areas across Europe (13, 14). Studies available on habitats at elevation describe them as isolated or island habitats, as compared to habitats at grade level. Green roof findings to date support the notion that island or rooftop habitats have become home to specific plants whose seeds have blown there or have been

deposited by visiting birds, invertebrates and other animals that can climb to access the green roof (13, 14, 31, 32).

Green roof studies in Switzerland and Canada have revealed that urban green roof habitats can mimic endangered ecosystems and restore habitat for species that were thought to have been lost to development and urban sprawl (11, 13, 14, 25). In Germany, over 20% of all endangered plants are arid/semi-arid grassland plants. These species are resistant to dryness, intense heat, frost, intense sunlight and wind – ironically all the conditions which prevail on a green roof. Habitat replacement for species at risk on green roof installations is a direction that ecologists and green roof planners are promoting (25, 29). Green roofs support many different prairie grassland species throughout the Midwest United States (60, 73) while others in Canada support rocky alvars from the Great Lakes Region (87, 90). Green roofs on the Mountain Equipment Co-op and York University Computer Science Buildings in Toronto, Ontario support prairie meadow species and several native Ontario grass species (87).

Frith and Farell of the UK's Greater London Authority Regeneration and policy team state:

> "green roofs of all types attract some wildlife. Natural colonization by a variety of lichens, mosses, plants and animals will occur over time, although they will be dependent on the roof's size, shape, aspect, location, climate and the species' mobility and tolerance. The use provision of shelter, nest and roost boxes and voids will also help to attract wildlife. We are only just beginning to realize the benefits of greening roofs for biodiversity." (29, 2003 p. 5)

Brienneisen's studies on biodiversity report findings of rare and common insect species on green roofs. This research is the most comprehensive to date on the study of habitat and biodiversity. Brienneisen studied samples of 11 extensive green roofs and found 172 species of beetle (10% of them in the Swiss Red Data Book of rare species) and 60 species of spider (40% of them equivalent to the Swiss Red Data Book) (13, 14). This research marked that older roofs had

species types and more numbers of species compared to younger newer roofs. Similarly, roofs with greater structural diversity or variances in topography (rocks, sticks, logs, berms, and other changes in elevation among the substrate) revealed the most diversity among species and a higher density of beetle species. This research also showed that the ability of the roof to retain water was a key factor in attracting species and that the number of rare beetles and spiders was increased on green roofs by varying the depth of substrate (13,14)

Extensive green roofs also offer safe havens for butterflies, which have been observed on roofs as high as 19th to the 23rd floor in England (43). English Nature), the British Government's Advisory Body on nature conservation, commissioned an invertebrate survey on existing green roofs across England (29). The study identified 14 animal species on green roof habitat and spawned a research group called 'Green Roofs for Black Redstarts' (31). This research partnership seeks to address the issue of conserving biodiversity and black Redstarts in London by rotecting brownfield land and the substrates therein that contain native seeds, invertebrate colonies and nesting grounds for Black Redstarts. Brownfields are the contaminated industrial lands that, according to the Government of the day, are preferred choices for development in preference to 'green land' which surrounds cities. There is an assumption that protecting green space is a better mechanism for supporting wildlife. Research by Gedge has shown that brownfield land is often more diverse than green field land (31). Gedge and the UK-based Biodiversity Partnership are asking green roof developers to consider utilizing brownfield substrates for green roof planting media (31, 32). The Biodiversity Partnership advocates for the use of industrial waste material as part of the green roof planting substrate and that it be allowed to rest at the building site during the early building phase. By resting the industrial waste on pallets close to the building site (at grade level), a local seed base and available invertebrate species can access the soil, build up and colonize once elevated to the roof. Otherwise, it is very difficult for some species to colonize these aerial locations. This ground level colonization process ensures that the

local biodiversity in the brownfield site are more easily replicated on the roof when the material is laid (31, 32).

The first such brown roof was constructed in Laban Dance Centre in Deptford and more are to follow across London. Another roof on the Creekside Centre, Deptford used a mix of crushed brick and concrete from a local source to provide the substrate base of the roof. In fact, this is how the black redstarts have been rejuvenated in London, England. Details of more than 15,000 square meters of green roofs are to be constructed for Black Redstarts over the next few years that are known about by the Partnership.

Air Pollution and Green Roofs
Research from the USDA Forest Service in Syracuse, New York, among others, support the role of urban forests, trees and shrubs in improving air pollution, reducing urban surface temperatures and improving property values in North American cities (74, 75, 79). Little research to date has isolated or reviewed the effect of green roofs on air pollution when added to commercial, residential or institutional buildings in urban areas. As shown throughout the literature review, many North American green roof research facilities investigate the effect of varying parameters on stormwater management, building energy and urban heat island effects; however, few studies to date have examined the role of green roofs in reducing air pollution in urban areas.

The Problem with Air Pollution
A study by Toronto Public Health Unit (2000) estimated that exposure to five common smog-related air pollutants contributed to over 1,000 premature deaths and about 5,500 hospitalizations each year in Toronto. One of the major components of smog is ground level ozone, a gas that is created when nitrous oxides (NOx) and volatile organic compounds (VOCs) mix with the atmosphere in sunlight. The Ontario Medical Association (OMA) reports that each day in Canadian cities we are exposed to a chemical "soup" that contains several poisons, particularly, ground level ozone and particulate matter, otherwise known

39

as acidic water droplets (83). The OMA estimates that air pollution costs Ontario more than one billion dollars per year from hospital admissions, emergency room visits and absenteeism. Health-related consequences of inhaling smog and particulates include; breathing difficulties, cardiac exacerbations, asthma, particularly in children, and sudden death, which peaks right after air pollution levels peak particularly in hot summer temperatures. According the OMA, levels of ozone and inhalable particulates are increasing in Ontario, despite warnings positioned at several levels of government. While public health responses to a predicted or sudden peak in air pollution levels can be planned at the municipal level, a bigger concern is the chronic, long-term effect of air pollution on residents in urban areas. It is well documented that air pollution can aggravate existing breathing and heart problems to such an extent that medical treatment is necessary (83). Of particular concern is asthma, which currently affects about 12% of children and 6% of adults in Canada (118).

Toronto-based hospitalization data reveal that children account for the largest number of asthma-related hospital admissions. This finding circumscribes the vulnerability of children to air pollution (118). Health researchers have developed risk coefficients to estimate the economic costs or burden of illness, associated with the lost productivity, risk of mortality, hospital admissions, emergency room visits, doctors office visits, medication costs and decreases in quality of life associated with air pollution. When these coefficients are applied to Toronto-specific data, the number of persons who are predicted to die or be hospitalized from air pollution levels contribute to about 1,700 premature deaths and 6,000 hospitalizations on an annual basis (118). This estimate is based on the health risks associated with exposure to ozone, nitrogen dioxide, carbon monoxide and sulphur dioxide, as well as the health risk associated with chronic exposure to fine particulates ($PM_{2.5}$).

The Economics of Air Pollution

The OMA estimates that air pollution contributed to 1,900 premature deaths, over 22,000 hospital visits and some 47 million minor illnesses in the year 2000 (84). To better estimate the economic and health damages associated with air pollution, the OMA developed a model called ICAP (Illness Costs of Air Pollution). In the year 2000, ICAP forecast that air quality in Ontario contributed $600 million in costs to the health-care system and another $560 million in direct losses to employers and employees. This represents over one billion dollars in direct costs to the people of Ontario (84). Conservative estimates of value for pain and suffering and loss of life add five billion and four billion dollars respectively to the total. These calculations predict a total annual economic loss of ten billion dollars in 2000 with a forecast that it will rise to twelve billion dollars by the year 2015.

Air Pollution and the Natural World

While air contaminants are a risk to human health, so too is their effect on the health and viability of the natural ecosystem. Air pollution can impact the sustainability of all living things, but in particular the integrity of built form in urban areas, the health and viability of lakes, rivers, agricultural and food growing areas, as well as the health of animals, invertebrates, fish and forests (57). Climate change and atmospheric variability are predicted to generate severe weather events and precipitate more frequent flooding and summer heat waves in Canada. Warmer average temperatures in cities will trigger the chemical reactions involved in smog formation and potentiate a rise in greenhouse gas emissions from coal-fired electricity plants as buildings respond with surges in air conditioning demand. Environment Canada predicts that the number of days when temperatures climb above 30 degrees Celsius will rise from 10 to 50 days per year if atmospheric carbon dioxide levels double (57).

Vegetation and Air Pollution

In response to urban environmental problems some authors have studied the effects of vegetation, particularly trees, on cooling ambient urban air, shading

buildings and absorbing gaseous air contaminants (4, 2, 6). Researchers in Los Angeles measured the effects of tree planting and re-roofing in cooler colours, on ambient temperatures and air pollution. Their research confirmed that combining trees with cool roofs could lower the ambient temperature in Los Angeles by $3° C$ and cool the air surrounding buildings (4). Cooler air in urban areas is more comfortable and reduces the vertical movement of warm, polluted air, hence concentrating the smog precursors in smaller volumes. Smog formation is accelerated when nitrogen oxides (NOx) react with volatile organic compounds that are released from the incomplete combustion of fossil fuels at high ambient temperatures (18). Akbari et al. calculated that daytime temperature reductions would decrease reliance on air conditioning and reduce emissions of NOx (nitrous oxides) from coal fired electricity plants for an estimated 10% reduction in smog precursors or a reduction of 350 tons of NOx per day (4). Los Angeles has a smog offset trading mark that trades NOx at 3,000$ per ton. To convert this to c/kWh of peak power, the researchers multiplied by 0.5kg/MWH to get .15c/kWh. Hence, the 350 tons/day of avoided "equivalent" NOx is then worth about one million US dollars per day to a city like Los Angeles (4).

Other researchers reported that air pollution levels are reduced when wind blown particulates (PM $_{2.5}$ and PM$_{10}$) stick to the leaves and stems of plants. Similarly, gaseous air pollutants can be dissolved or sequestered, particularly carbon dioxide, through stomata on plant leaves (64, 65, 76, 77, 78). Johnson et al. estimated that 2,000 square meters of un-mowed grass on a roof could remove as much as 4,000 kg of particulates in their leaves and stems (43). Peck cites German research (un-translated) and suggests that one square meter of uncut grass on a roof would create enough oxygen to meet the needs of one human over one year (67). More recently, Tan and Sia sampled roof temperatures, roof glare and other air quality parameters both pre- and post-green roof installation in Singapore (105). They used light sensors, mini-volume aerosol samplers, particle counters, an aethalometer for black carbon mass concentration and an HOBO weather station to report that acidic gaseous pollutants, glare, ambient green roof

surface temperatures and black carbon mass (or soot) levels all dropped significantly after the installation of the green roof. This research supports the notion that further use of urban vegetation in any form would be a benefit to urban air quality (105).

Conclusion

Given this significant and growing body of global green roof literature, it seems obvious that green roofs contribute positively to a myriad of complex environmental problems associated with densely populated urban areas. Benefits include the reduction of ambient urban surface temperatures or urban heat island reduction, reduction in heat flux into buildings, improvements to stormwater runoff quantity and quality, protection of roof membranes, habitat restoration with species conservation and reduced building energy demand in low rise or commercial buildings, particularly in the summer months. Nonetheless, more specific research is required to support the potential benefits of green roofs and their role in mitigating urban air pollution.

Currently, it is hypothesized that adding urban vegetation, particularly green roofs, will reduce the level of gaseous pollutants measured in urban air. By extension improved air quality would eventually provide a benefit to human health and potentially save lives. Ultimately, adding vegetation to urban surfaces might reduce the public health costs associated with increased doctor's visits, hospitalizations and pharmaceuticals that result from poor air quality in urban areas (118, 57, 83, 84).

The following research will address the current gap in research on quantifying the effect of green roofs on urban air quality. The study will investigate the effect of adding different types of roof top vegetation through a variety of scenarios in a study area located in Midtown Toronto, Ontario, Canada. It is beyond the scope of this investigation to quantify the effects of improved air quality on human health outcomes and the economics of health care.

CHAPTER 4: METHOD

Study Method

It is well known that trees, shrubs and other natural vegetation affect urban air contaminant levels, and, by extension, air quality and the overall experience of health and well-being of humans living in urban areas (2, 6, 7, 16, 17). Quantifying the contribution of green roofs in reducing air contaminant levels within an urban neighbourhood, however, is a relatively new application within the emerging discipline of green roof study.

A geographic study area known as Midtown was selected within the Greater City of Toronto. Midtown is constituted by parts of Ward, 22 (St. Pauls), Ward 27 (Toronto central-Rosedale) and Ward 20 (Trinity Spadina) and bounded by Spadina Avenue in the west, Bloor Street in the south, Eglinton Avenue in the north and the Don Valley ravine, Bayview Avenue, Moore Street, Frobisher Street and Chaplin Street in the east.

In order to complete this study, previous research by Kenny on the economic and environmental profile played the urban forest in Midtown was scrutinized (44). Kenny quantified the urban forest characteristics that could be estimated by the four main modules (A, B, C, and D) within the UFORE (Urban Forest Effects) Model. In consultation with the UFORE modellers in Syracuse, New York, Kenney collected data from 72 randomly selected on-the-ground study plots within the Midtown neighbourhood as per the UFORE field collection tool (77). Kenny's report provided a profile or urban forest health and a subsequent analysis that forestry managers in the City of Toronto still use today (44).

This researcher obtained permission from Kenny to utilize the original criterion plot data from the 72 randomly selected plots in Midtown. Using UFORE – D. The researcher was able to manipulate specific data elements and develop scenarios to investigate the effect of urban vegetation, particularly green roofs on air contaminants levels in Midtown. The researcher visited the 72 randomly

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selected plots in Midtown by using GPS coordinates and on-the-ground plot maps to collect each plot's municipal address, verify vegetation, type of buildings and other plot features that were deemed relevant to the study.

Figure 10: Toronto Wards
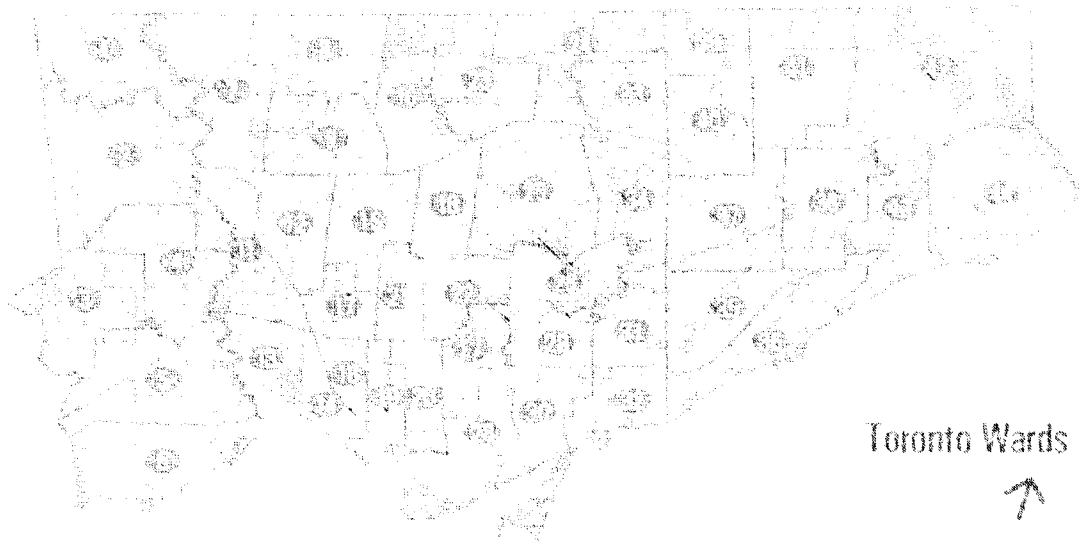
[Adapted Map, of City - Toronto Wards (2001). Map Library, University of Toronto, with Midtown study area highlighted in yellow, from www.toronto.ca]

Each sample plot was circular with a radius of 11.287 meters and provided a total surface area of 400 m² or 0.04 ha per plot. The total sampled area was 28.800 m² or 2.88 ha within Midtown. The total area of the Midtown neighbourhood was approximately 1,216 ha within the City of Toronto. Plots were selected from land-use types by randomly selecting points from a 50 m x 50 m grid, overlaid on a GIS-based map of Midtown, using Arc View GIS 3.1. Colour orthophotos of the area were analyzed using Arc View GIS 3.1 to calculate plot details as required. Each orthophoto was examined separately at a scale of approximately 1:5000. Within each plot, a forest surveyor's transit was utilized to determine the co-ordinates of each feature within the plot relative to a GPS-established plot center (44). Using this method, the UTM (Universal Transverse Mercator) co-ordinates of each plot center were known by the researcher.

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Figure 11: Sample Plot in Midtown
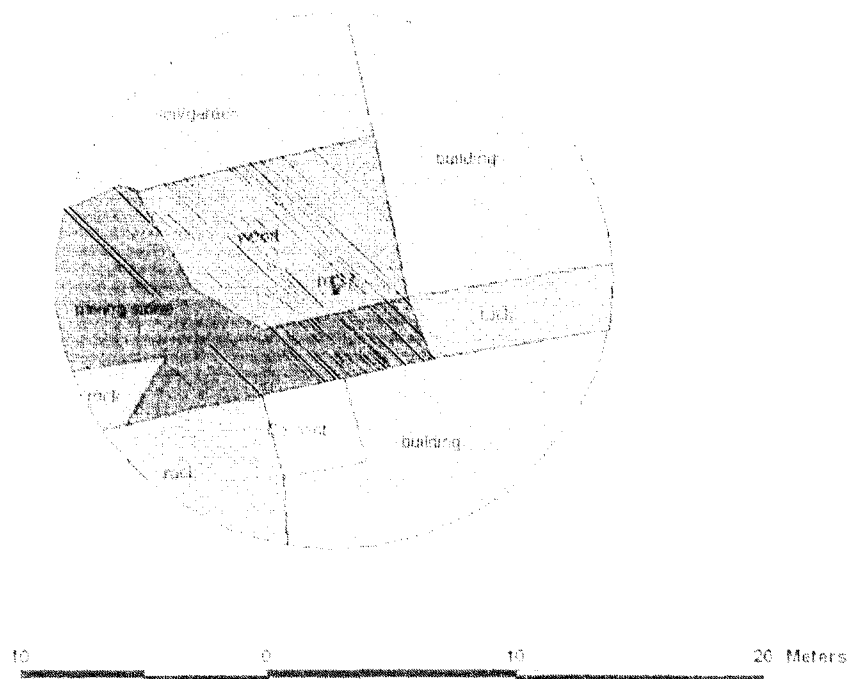
The method for plot classification within Midtown was developed by Nowak and Crane at the United States Department of Agriculture (77). Midtown was stratified into eight land-use classes: low, medium and high residential; commercial; industrial; institutional; unclassified; and open areas, including parks, ravines, cemeteries, transportation corridors and golf courses. These categories were derived from GIS data obtained from CanMap ® Streetfiles V2.0 from DMTI Spatial 2000 (44).

UFORE Computer Model
The Urban Forest Effects (UFORE) computer model was developed to help forestry managers and researchers quantify urban forest structure, function, and vulnerability to pest invasion based on standard inputs of field, meteorological and pollution data.

In this research, a UFORE-based field collection tool guided researchers on the collection and measurement of plot features such as buildings, amount of cement, tar, impervious material, soil, rock, duff/mulch, herbaceous, grass, wild grass, water, shrubs and other ground cover (44). Other plot features were recorded as point items including: trees; shrubs; telephone poles; light standards; traffic signs; sewer grates; fire hydrants and other above ground point utilities; or as polygons with each vertex recorded: shrub beds; grass; wild grass; soil; duff/mulch; herbaceous (excluding grass and shrubs); water; buildings; asphalt; cement; rock; wood; and other impervious material.

On each of the 72 plots, the following additional information was recorded:
- Land use
- Plot tree cover (%)
- Ground cover (%)
- Building information (wall material, roof material, building height in meters)
- Shrub information (species, height (meters), percent missing, and percent of coverage of the plot)
- Tree information including species, diameter at breast height (dbh) taken at 1.37 meters, total height, bole height – height to base of live crown, crown width, missing crown, health of tree and distance to buildings (44).

The UFORE D computer model also necessitated the collection manipulation of one year of local hourly meteorological data and air pollutant concentration measurements from the City of Toronto. Meteorological data and air pollutant concentration data from Toronto in 1998 was used for this study for several reasons. Firstly, it was 1998 Toronto data that was used in the Kenny study in 2001. The meteorological data had been collected for use by the UFORE model and then stored at the Northeastern Forest Research Station in Syracuse, New York. The 1998 meteorological data was easily accessed and utilized by this researcher. The UFORE modellers recommended that the researcher use this 1998 Environment Canada meteorological and pollutant data from Toronto as a

significant amount of time had already been dedicated to its manipulation to fit the requirements of the UFORE model for the Kenny study (44). Nonetheless, the use of 1998 hourly meteorological data marks a limitation in the study. If possible, a profile of local hourly meteorological data and air pollutant concentrations from 2004 within the Midtown neighbourhood itself would have produced a more accurate pollutant analysis for the current study.

There are several modules within the UFORE computer model that facilitate research. They include:

UFORE-A: Anatomy of the Urban Forest – quantifies urban forest structure (species composition, density, tree health, leaf area, leaf and tree biomass).

UFORE-B: Biogenic Volatile Organic Compound (VOC) emissions – quantifies hourly urban forest VOC emissions (isoprene, monoterpenes and other VOC emissions that contribute to ozone formation) and ozone and CO formation based on VOC emission.

UFORE-C: Carbon Storage and Sequestration – calculates total carbon (C) storage potential and gross and net C sequestered annual by the urban forest based on field data.

UFORE-D: Dry Deposition of Air Pollution – quantifies the hourly amount of pollution removed by the urban vegetation and the associated per cent improvement in air quality through out a year. Pollution removal is calculated for O_3, SO_2, NO_2, CO and PM_{10} (74, 77, 75, 6).

UFORE-D
UFORE-D calculates the level of dry deposition of air pollution, (that is, the amount of pollution removed during non-precipitation periods) on urban

vegetation. The module also estimates the hourly dry deposition of O_3, SO_2, NO_2, CO and PM_{10} on urban vegetation throughout a year. UFORE calculations are based on vegetation cover data, hourly weather data and pollution concentration data. This hourly weather and pollution data were collected and collated from three Environment Canada weather stations: Toronto's Pearson International Airport; Buttonville Airport; Richmond Hill; and Toronto Island Airport in downtown Toronto. The researcher chose one year of hourly pollution data from Environment Canada data due to the logistics of converting hourly data to a UFORE-compatible format.

Figure 12: UFORE- D and Plants
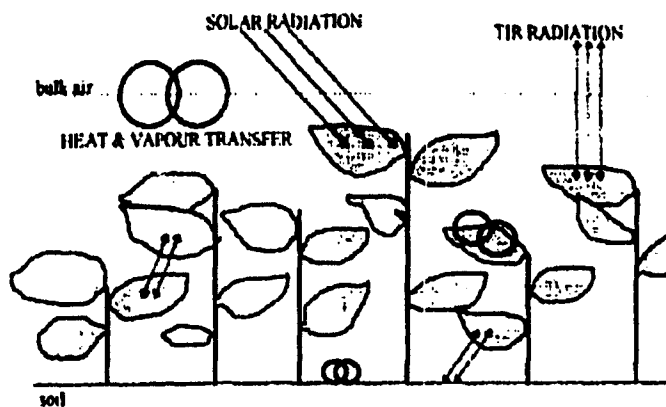
(Del Barrio (1998) (23) p. 184)

In this basic green roof schemata, note that several natural systems occur simultaneously between the atmosphere and the surrounding green roof canopy. Firstly, solar energy is delivered by the sun and this activates a plant's internal energy system. This heat energy drives many cellular processes like photosynthesis, evapo-transpiration and the opening and closing of stomata themselves. Leaf stomata act at doorways into internal plant structures and determine what air contaminants or particulates to accept or reject. Gaseous air contaminants flow down a diffusion gradient through the leaf stomata and into the internal plant structures. Heat energy can be transferred within and between the leaves and the soil on the ground below and the surrounding air via longwave

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radiation (shown as TIR radiation in figure 12). Evapo-transpiration also occurs within leafs via three phenomena: water evaporates inside the leaves via stomatal cavities; vapour diffuses up to the leaf surface; and convective vapour transport occurs from the leaves to the surrounding air as each leaf cell controls its own moisture levels within and outside their cellular environment and the surrounding atmosphere. Finally, there is an element of heat and vapour transfer to and from the soil layer beneath the plant canopy (23).

UFORE-D derives pollution outputs by using the hourly pollution input data from Environment Canada combined with predicted or default plant species measurements derived from known systems to estimate the amount of air contamination a particular leaf will absorb. Calculations are aggregated in order to predict pollution reductions over given vegetated surface areas. UFORE D utilizes daily hourly temperatures, humidity, barometric pressures, hourly pollutants, plant surface areas, and many other characteristics including height, species, general health, leaf area index, to determine calculations as explained below.

Calculations in UFORE-D

In UFORE-D the pollutant flux (F; in $g\ m^{-2}\ s^{-1}$) is calculated as the product of deposition velocity (V_d; in $m\ s^{-1}$) and the pollutant concentration (C; in $g\ m^{-3}$):

$$F = V_d{}^*C$$

Deposition velocity is calculated as the inverse of the sum of the aerodynamic resistances (R_a) + laminar boundary layer (R_b) + canopy (R_c) resistances:

$$V_d = (R_a + R_b + R_c)^{-1} \qquad (5);$$

Hourly meteorological data were used in estimating R_a and R_b. The aerodynamic resistance is calculated as (45):

$$R_a = u(z)^* u_*^{-2}$$

where $u(z)$ is the mean windspeed at height z (m s^{-1}) and u_* is the friction velocity (m s^{-1}).

$$U_* = (k^* u(z-d))[\ln((z-d)^* z_o^{-1}) - \Psi_M((z-d)^* L^{-1}) + \Psi_M(z_o^* L^{-1})]^{-1}$$

where k=von Karman constant, d=displacement height (m), z_o=roughness length (m), Ψ_M=stability function for momentum, and L=Monin-Obuhkov stability length. L was estimated by classifying hourly local meteorological data into stability classes using Turner classes and then estimating $1/L$ as a function of stability class and z_o (70).

When $L < 0$ (unstable):

$$\Psi_M = 2\ln[0.5(1+X)] + \ln[0.5(1+X^2)] - 2\tan^{-1}(X) + 0.5\pi$$

where $X = (1 - 28zL^{-1})^{0.25}$ (4).
When $L > 0$ (stable conditions):

$$u_* = C_{DN} u^* \{0.5 + 0.5[1 - (2u_o/(C_{DN}^{1/2*} u))^2]^{\frac{1}{2}}\}$$

where $C_{DN} = k(\ln(z/z_o))^{-1}$; $\upsilon_o^2 = (4.7 z \lozenge \theta_*)T^{-1}$; g=9.81 m s^{-2}; $\theta_* = 0.09(1 - 0.5N^2)$; T=air temperature (K^o); and N=fraction of opaque cloud cover (108, 109). Under stable conditions, υ_* was calculated by scaling actual windspeed with a calculated minimum windspeed based on methods given in EPA (1995) (109).

The quasi-laminar boundary-layer resistance was estimated as (89):

$$R_b = 2(Sc)^{2/3}(Pr)^{-2/3}(k^* u_*)^{-1}$$

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where k=von Karman constant, Sc=Schmidt number, and Pr is the Prandtl number.

In-leaf, hourly tree canopy resistances for O_3, SO_2, and NO_2 were calculated based on a modified hybrid of big-leaf and multilayer canopy deposition models. Canopy resistance (R_c) has three components: stomatal resistance (r_s), mesophyll resistance (r_m), and cuticular resistance (r_t), such that:

$$1/R_c = 1/(r_s + r_m) + 1/r_t$$

Mesophyll resistance was set to zero s m^{-1} for SO_2 (20) and 10 s m^{-1} for O_3 (41). Mesophyll resistance was set to 100 s m^{-1} for NO_2 to account for the difference between transport of water and NO_2 in the leaf interior, and to bring the computed deposition velocities in the range typically exhibited for NO_2 (52). Base cuticular resistances were set at 8,000 s m^{-1} for SO_2, 10,000 s m^{-1} for O_3, and 20,000 s m^{-1} for NO_2 to account for the typical variation in r_t exhibited among the pollutants (52).

Hourly inputs used to calculate canopy resistance are photosynthetic active radiation (PAR; μ E m^{-2} s^{-1}), air temperature (T_a), windspeed (s m^{-1}), u (s m^{-1}), CO2 concentration (set to 360 ppm), and absolute humidity (kg m^{-3}). Air temperature, windspeed, u, and absolute humidity are measured directly or calculated from measured hourly meteorological data. Total solar radiation is calculated based on the METSTAT model with inputs from the meteorological data set (63). PAR is calculated as 46 percent of total solar radiation input (68, 69).

As CO and removal of particulate matter by vegetation are not directly related to transpiration, R_c for CO was set to a constant for in-leaf season (50,000 s m^{-1}) and leaf-off season (1,000,000 sm^{-1}) based on data from (12). For particles, the

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median deposition velocity from the literature (8) was 0.0128 m s^{-1} for the in-leaf season. Base particle V_d was set to 0.064 based on a LAI of 3 and a 50-percent re-suspension rate of particles back to the atmosphere (122). The base V_d is adjusted according to actual LAI and in-leaf versus leaf-off season parameters.

Pollution Deposition

Particle collection and gaseous deposition on deciduous trees in winter assumed a surface-area index for bark of 1.7 (m^2 of bark per m^2 of ground surface covered by the tree crown) (74). To limit deposition estimates to periods of dry deposition, deposition velocities were set to zero during periods of precipitation.

Hourly pollution concentrations (ppm) for gaseous pollutants in Toronto were obtained from the Ministry of the Environment (6 monitors at 3 sites). Hourly ppm values were converted to μ g m^{-3} based on measured atmospheric temperature and pressure. Average daily concentrations of PM_{10} (μ g m^{-3}) were also obtained from the Ministry of the Environment (6 monitors at 3 sites). Missing hourly meteorological or pollution-concentration data were estimated using the monthly averages for that specific hour.

Average hourly pollutant flux (g m^{-2} of canopy coverage) among the pollutant monitoring sites was multiplied by Midtown's grass coverage (m^2) to estimate total hourly pollutant removal across Midtown. Bounds of total removal of O_3, NO_2, SO_2, and PM_{10} were estimated using the typical range of published tree and shrub in-leaf dry deposition velocities (52).

To approximate boundary-layer heights in the study area, mixing-height measurements were used. Daily morning and afternoon mixing heights were interpolated to produce hourly values using the EPA's PCRAMMIT program (108). Minimum boundary layer heights were set to 150 m during the night and 250 m during the day based on estimated minimum boundary layer heights in cities. Hourly mixing heights (m) were used in conjunction with pollution

concentrations (μ g m $^{-3}$) to calculate the amount of pollution within the mixing layer (μ g m $^{-2}$). This extrapolation from ground-layer concentration to total pollution within the boundary layer assumes a well-mixed boundary layer, which is common in daytime (unstable conditions) (15). The amount of pollution in the air was contrasted with the amount removed by the vegetation on an hourly basis to calculate the relative effect of vegetation in reducing local pollution concentrations as shown by:

$$E=R(R+A)^{-1}$$

where E = relative reduction effect (%); R = amount removed by vegetation (kg); A = amount of pollution in the atmosphere (kg).

The ability of individual vegetation (trees, shrubs and grass) to remove pollutants was estimated for each diameter class using the formula (79):

$$Ix=R_t(LAx/Lat)/Nx$$

where I x = pollution removal by individual units e.g. trees in diameter class x (kg/tree); R_t = total pollution removed for all diameter classes (kg); LAI = total leaf area in diameter class x (m2); LAI = total leaf area of all diameter classes (m ^{2}); and Nx = number of trees in diameter class x. This formula yields an estimate of pollution removal by individual trees, shrubs and grass based on leaf surface area (the major surface for pollutant removal).

Scenario Development

The researchers created seven scenarios that represented simulations of natural vegetation levels within the Midtown Toronto study area. These varying amounts of natural vegetation were created by manipulating the number of trees, shrubs and grass species within the 72 study plots in Midtown. UFORE-D was used to quantify the impact of varying urban vegetation on air pollutant levels. Air

pollutant levels affected by vegetation that can be simulated by UFORE-D include: carbon dioxide, sulphur dioxide, nitrous oxide, ozone, and carbon monoxide as well as particulate levels for example, dust and lead.

Scenario 1
BASELINE: this scenario was based on the reductions in pollutants provided by existing trees and shrubs in Midtown.

Scenario 2
Green Walls: this scenario examined the effect on air pollutant reductions in Midtown when existing trees and shrubs were removed and vertical "hedges" or walls of Juniper[2] species were added within 3 meters of residential (medium and low) houses.

Scenario 3
No Big Trees: this scenario examined the effect on air pollutant reductions in Midtown when all big trees with a diameter-at-breast-height > 22cm were removed.

Scenario 4
No Trees: this scenario examined the effect on air pollutant reduction in Midtown when all trees were removed and only shrubs remained. In some data runs, shrubs were replaced on flat roofs ie. commercial, institutional and high residential in Midtown.

Scenario 5
Trees off Buildings: this scenario examined the effect on air pollutant reduction in Midtown when trees that provided shade to buildings (within 3-5 meters) were removed.

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[2]Walls of Juniper trees were chosen to represent a green wall, as UFORE is able to estimate the impacts of this green wall on energy consumption, which was utilized in a parallel study. Although vines can be selected for green walls, UFORE does not simulate the impacts of vines on energy consumption. Vines would not have a significantly different impact on air quality as their LAI is similar to that of the Juniper species selected for the green walls.

Scenario 6

Trees Low Residential: this scenario examined the effect on air pollution in Midtown when baseline trees and shrubs were augmented with an extensive green roof or grass application on commercial, industrial, high residential and institutional buildings. The surface area available for this grass or green roof application represented approximately 9% of surface area within the 72 sample plots and was derived by summing the total building surface areas in each plot with a predicted flat roof. For purposes of this research, it was assumed that these roofs would be structurally sound for a green roof application.

Scenario 7

Grass Roofs: this scenario examined the effect on air pollution in Midtown when baseline trees and shrubs were augmented with an extensive green roof or grass application on all available buildings in Midtown. Hence roof surface areas were calculated by summing all building surface areas in the 72 plots including, commercial, industrial, institutional, low, medium and high residential buildings. The surface area consumed by buildings was approximately 20% of the total plot surface area available in Midtown. This was approximately double the surface area available for green roofs compared to scenario 6. For purposes of this research, it was assumed that these roofs would be structurally sound for a green roof application.

Data obtained from the manipulations of these aforementioned scenarios will be discussed in the results section of the report.

Limitations of UFORE Model

For the grass roofs scenario, the V_d was adjusted based on a predicted LAI of 3 for grasses (79). The model is programmed for individual species of tree and shrub LAI data as well as the predicted percent tree and shrub leaf areas calculated from UFORE-A data. Local leaf-on and leaf-off dates are given to the model so that deciduous-tree transpiration and related pollution deposition are

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limited to the in-leaf period; seasonal variation in removal can be illustrated for each pollutant. As the main interest in this study was a grass-only scenario, UFORE was set to a local leaf-on deciduous tree-transpiration rate for the Canadian in-leaf period. The leaf-on and leaf-off dates were adjusted to represent Canadian deciduous-tree transpiration and related pollution deposition in the in-leaf period. This represents the main experimental portion of the study, and hence a limitation. The UFORE model is biased toward scientific default values for all tree and shrub species values that are available in the model.

As mentioned previously, the study would have been more accurate had local Environment Canada meteorological and air contaminant data been collected at a weather station within the Midtown study area. Instead, Environment Canada data from 1998 was used to provide air pollution estimations in the study.

Another limitation was that the dollar values associated with the removal of pollutants over the year were provided by an externality process not well explained to the researcher. The monetary values were based on American externality values that were derived from work done by Murray (1994) in New York State's energy department. These values incorporate the perceived cost to society of pollution emissions based on predicted air pollution consequences to health and the environment. Although the relative dollar values are applicable to other regions, the exact values, even using Murray's assumptions, would most likely differ between countries with different government priorities for funding health care. There are other limitations including the UFORE model's inability to predict reduced building energy demand from green roofs. These limitations reduce the scope of using the UFORE to assess the overall benefits of green roofs, however, a fuller critique of the UFORE model is beyond the scope of this study.

CHAPTER 5: RESULTS

Results of the study are presented in figures 13 - 18 below. Throughout figures 13-17, the histograms illustrate the UFORE model's estimates among scenarios and vegetation groupings concerning the amount of a particular air contaminant that was reduced. The air contaminants in the model here included: carbon monoxide, nitrogen dioxide, sulphur dioxide, ozone and particulate matter. In figure 18, the histogram reflects the amount of US$ predicted to be associated with the overall reduction of the five major air contaminants measured by the UFORE model. The vegetation groupings were described in more detail in the method section above.

As might be predicted, the UFORE model illustrates that trees and shrubs remove air contaminants more effectively when compared to other vegetation groupings. Further, when trees are compared with shrubs, trees out-perform shrubs in their ability to reduce pollutants. This result is expected, based on the number of functioning leaf units that provide maximal surface area in contact with air and particulates. Despite the strong performance of trees and shrubs, it is neither practical nor plausible to seed most elevated roof surfaces with these heavy, tap and fibrous-rooted species.

The UFORE model illustrated that when grassy species were added to selected vegetation groupings, they too contributed to air contaminant reductions. Adding grass resulted in significant reductions across all five air contaminant levels measured by the UFORE model. Grass was chosen as a proxy unit for green roofs not only because it is are a known quantity in seed mixtures for green roof planting but also because the UFORE model was able to predict a leaf area index and evapo-transpiration rates in its calculation of air pollution values (Figures 13-17).

Also of note throughout figures 14-17 are the results for scenarios with 'No Trees'. In figures 14-17, shrubs data were augmented by 9% in Midtown by adding equal surface area of shrubs to buildings with flat roofs -just as was done in scenario 6. Results indicate that a significant amount of air pollution is mitigated across contaminant groups when shrubs alone are at work in Midtown. This is a noteworthy finding in that shrubs are lighter, portable, are both evergreen and deciduous and can be placed among other appropriate plant groupings on extensive roofs in urban areas.

In figure 18, the histogram illustrates a derived monetary value for each air contaminant removed by trees, shrubs and grass on roofs in the seven scenarios created by the researcher. These values were estimated using a median externality value for the United States based on calculations by Murray et al. (1994). The following values were set as default in the UFORE-D module and were based on dollars per metric ton (t):

$$NO_2 = \$6,752 \ t^{-1}, PM10 = \$4,508 \ t^{-1}, SO_2 = \$1,653 \ t^{-1}, \text{ and } CO = \$959 \ t^{-1}.$$

Externality values for O_3 were set to equal the value for $NO_2 = \$6,752 \ t^{-1}$ (71).

These results illustrate that a significant amount of air contamination is contained by the natural systems contained in trees, shrubs and grass species on roofs. Air contaminant reductions that would accompany the addition placement and installation of vegetation in urban areas would help achieve Canadian Kyoto Protocol objectives, and serve to improve the quality of life and health of all citizens in urban communities.

Figure 13: Total CO removal (Mg) by trees, shrubs and grass in Midtown per Annum

Total CO removal (Mg) by trees, shrubs and grass in Midtown
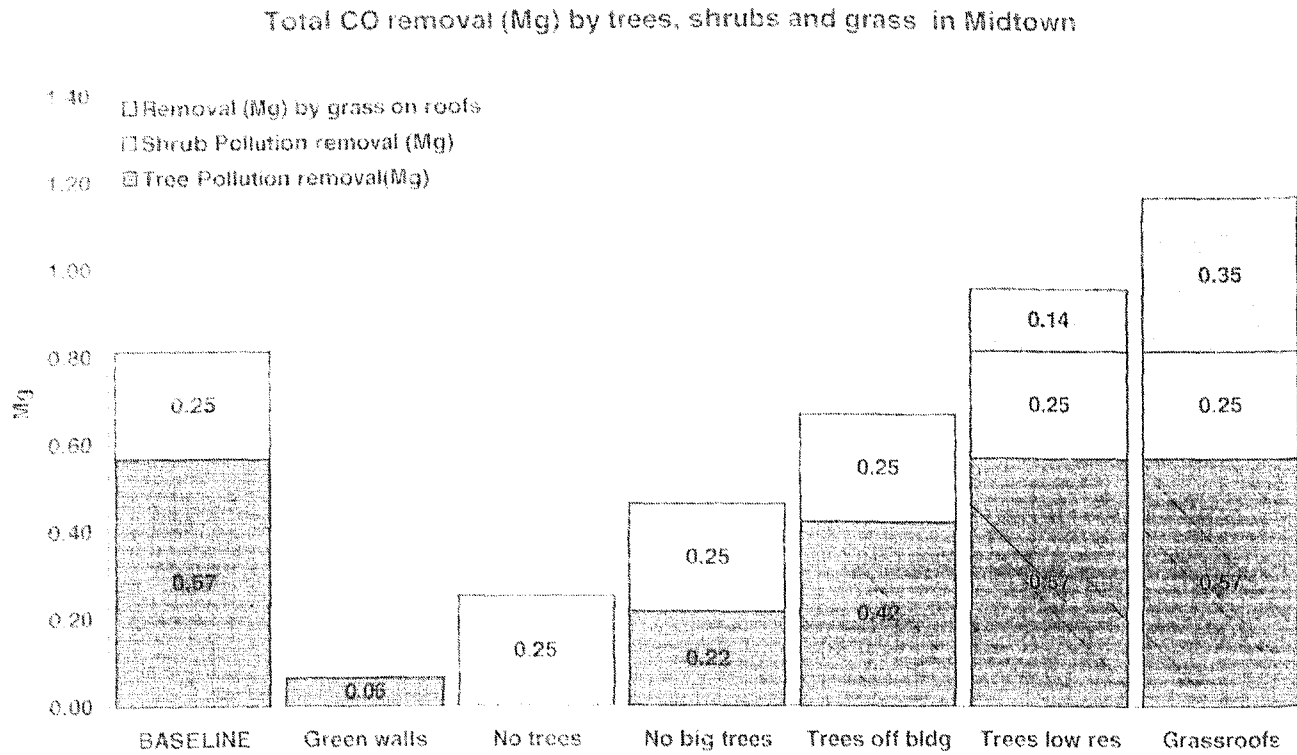
Figure 14: Total NO₂ removal (Mg) by trees, shrubs and grass in Midtown per Annum

NO2 removal (Mg) by trees, shrubs and grass in Midtown

Legend:
- Removal (Mg) by grass on roofs
- Shrub Pollution removal (Mg)
- Tree Pollution removal(Mg)

Data values by category:

Category	Values
BASELINE	1.67 / 3.74
Green walls	0.62
No big trees	1.67 / 1.23
No trees	2.91
Trees off bldg	1.67 / 2.78
Trees low res	0.65 / 1.67 / 3.74
Grassroofs	1.60 / 1.67 / 3.74

Y-axis: Mg (0.00 to 8.00)
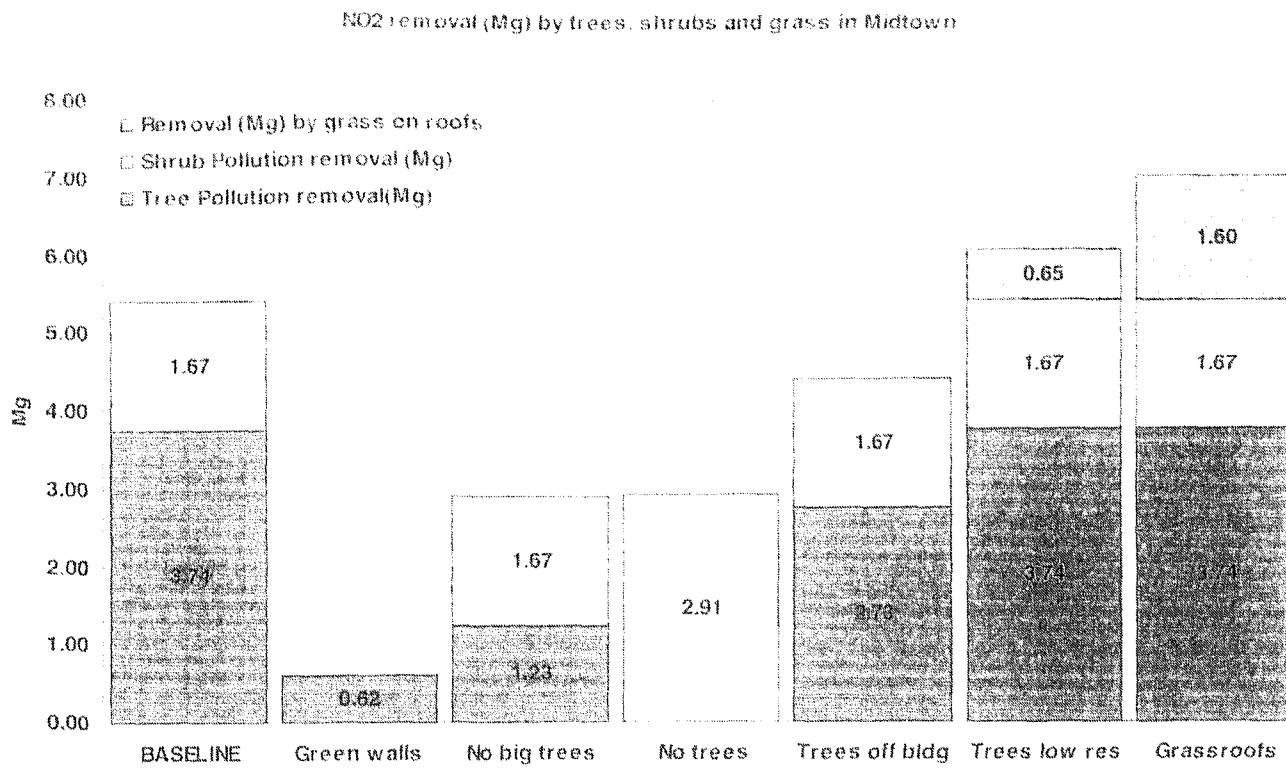
Figure 15: Total O₃ removal (Mg) by trees, shrubs and grass in Midtown per Annum

O₃ removal (Mg) by trees, shrubs and grass in Midtown
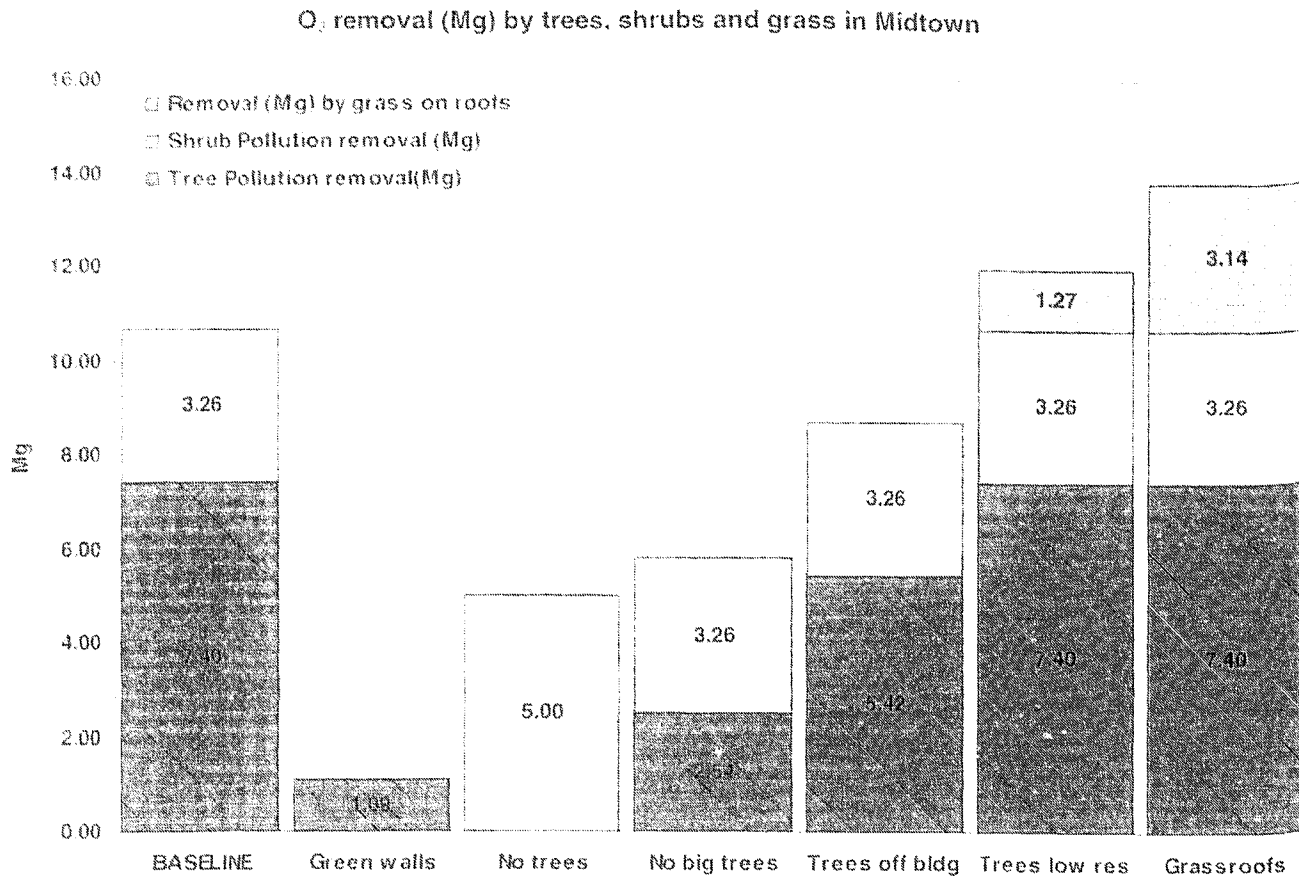
Figure 16: Total PM$_{10}$ removal (Mg) by trees, shrubs and grass in Midtown per Annum

PM10 removal (Mg) by trees, shrubs and grass in Midtown

Legend:
- ☐ Removal (Mg) by grass on roofs
- ☐ Shrub Pollution removal (Mg)
- ☐ Tree Pollution removal(Mg)

Y-axis: Mg (0.00 to 12.00)

Categories: BASELINE, Green walls, No big trees, Trees off bldg, No trees, Trees low res, Grassroofs

Values shown:
- BASELINE: 2.69, 5.57
- Green walls: 1.37
- No big trees: 2.69, 1.70
- Trees off bldg: 2.69, 4.06
- No trees: 7.17
- Trees low res: 0.88, 2.69, 5.57
- Grassroofs: 2.17, 2.69, 5.57
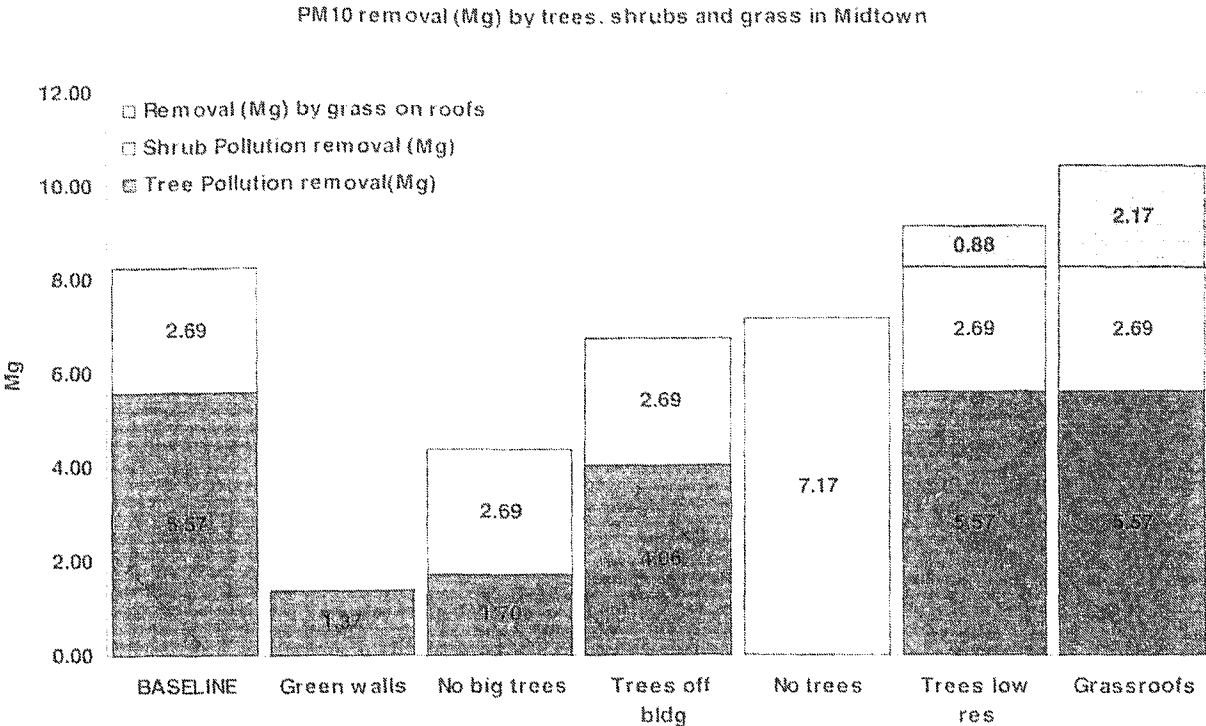
Figure 17: Total SO$_2$ removal (Mg) by trees, shrubs and grass in Midtown per Annum

SO2 removal (Mg) by trees, shrubs and grass in Midtown

□ Grass Pollution removal (Mg)
□ Shrub Pollution removal (Mg)
▨ Tree Pollution removal(Mg)
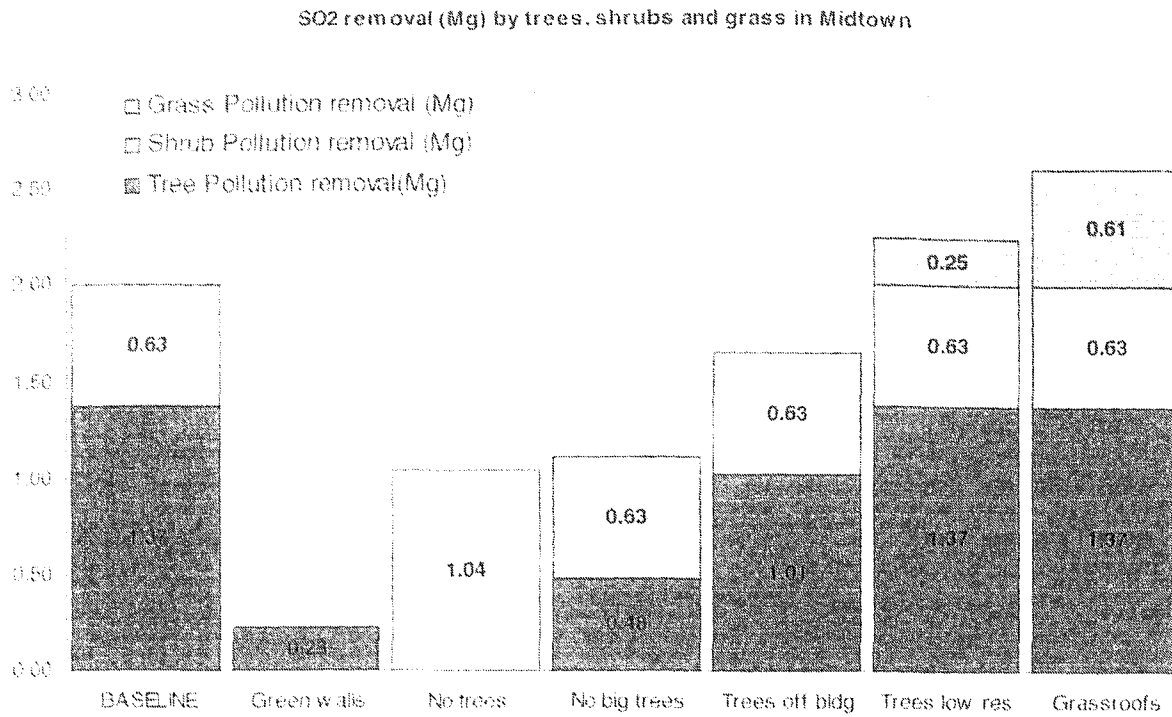
Figure 18: Total pollution removal value (US$) by trees, shrubs and grass in Study Area per Annum

Total pollutant removal value ($) by trees, shrubs and grass (rooftops) in Midtown.
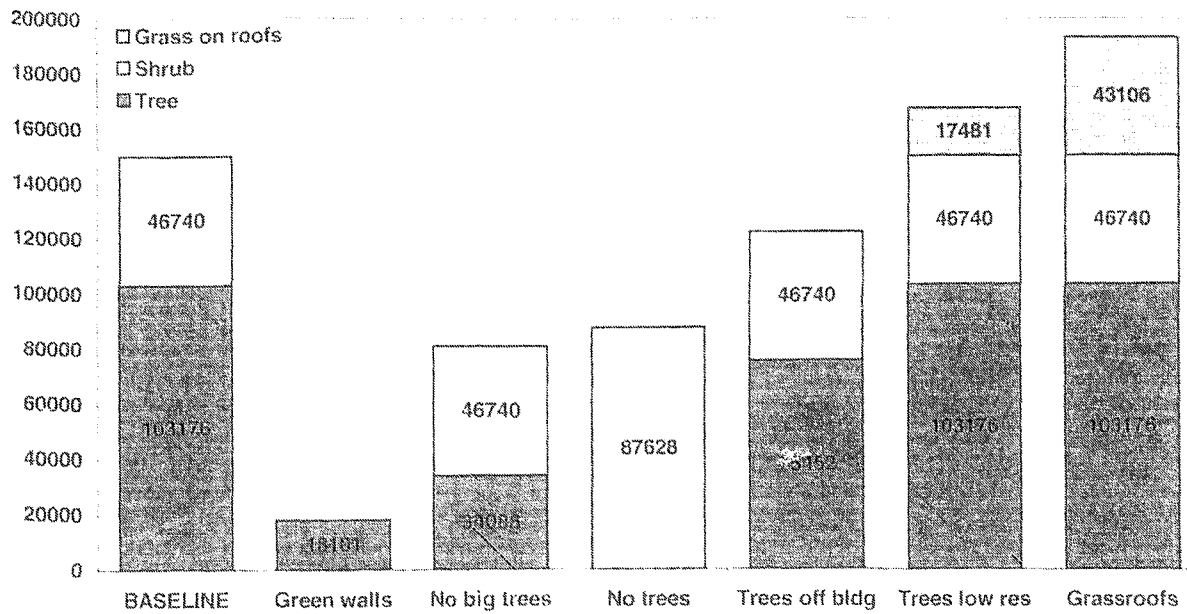
Figure 19: Proportional Removal Values for the Effect of Grass Roofs on Air Contaminants in Midtown per Annum

Proportional removal values for CO, NO_2, O_3, PM_{10} and SO_2 in Midtown with grass roofs.

SO2 CO
2% 1%

PM10
24%

NO2
25%

O3
48%

CO
NO2
O3
PM10
SO2
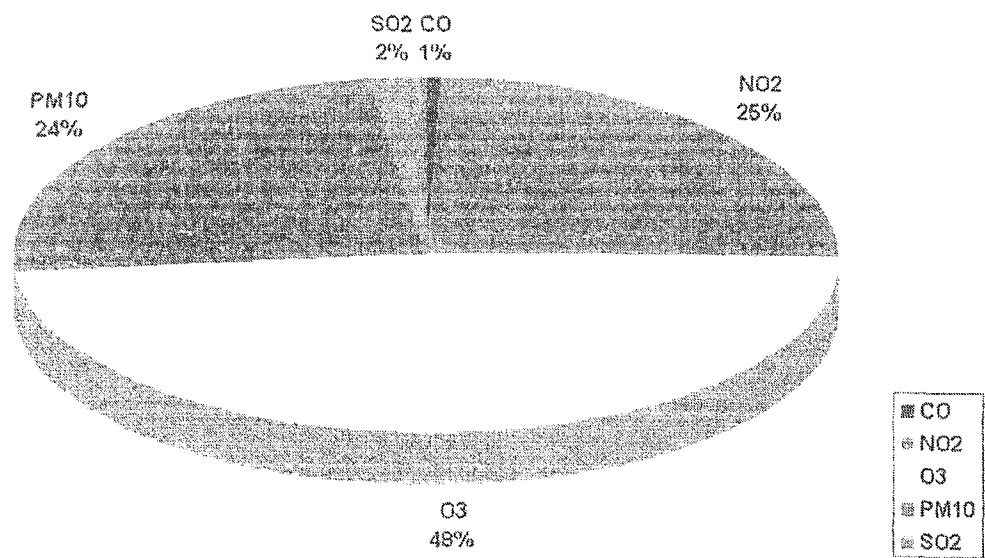
Chapter 6: Discussion

The results of this study clearly demonstrate that when roof surfaces are installed with green roofs or an application of grass on roofs there is a significant reduction in air contaminant levels over one year in Midtown. The UFORE model reports that across all 7 vegetation scenarios there are significant reductions in CO, NO_2, SO_2, PM_{10}, CO_2 and ozone levels in Midtown over one year. Trees, however, clearly out perform shrubs and grass on roofs when comparing the amount of air contaminants reduced in Midtown over one year. This is not surprising given the large surface area provided by tree leaves compared with smaller shrubs and even smaller grass species. Shrubs however, were clearly a strong performer in the reduction of contaminants as well.

When grass was placed on every available building roof surface (approximately 20% of plot surface areas including low and medium residential or sloped roofs) as shown in scenario 7, air contaminant reductions were more than twice the amount of those in scenario 6. In scenario 6, grass was applied to approximately 9% of plot surfaces as represented by flat roofs on commercial, industrial, institutional and high residential buildings. Scenario 6 presents a more realistic estimate of air contaminant reduction within a neighbourhood as green roof placement is better suited to flat roofs. Building owners and developers are more likely to install green roofs on buildings with flat roofs that are deemed structurally adequate to support the added weight of a green roof. As mentioned in the literature review, green roofs are best placed on flat roofs with a slope of less than 25%; nonetheless, slopes up to this range have proven equally beneficial to the environment in European studies to date. As future building codes and green roof policies come to fruition in Toronto, and Canada, prescribed green roof design parameters including type of growing media, depth of media, choice of plant species and slope of roof will serve to maximize the environmental benefits prioritized within a particular jurisdiction.

Of particular note in the results section is that the level of carbon monoxide removed by grass roofs exceeds the level of carbon monoxide removed by shrubs over one year in Midtown. Grass on every Midtown roof (scenario 7) removed 0.35 Mg of CO per annum compared to 0.25 Mg by existing shrubs. Further, the amount of NO_2 removed by grass on roofs (scenario 7) at 1.60 Mg per year was comparable to levels reduced by shrubs at 1.67 Mg per annum. For ozone and PM_{10} grass on every roof (scenario 7) performed comparably well at 3.14 Mg of ozone and 3.26 Mg for shrubs over one year in Midtown. Similarly for PM_{10}, while grass of roofs proved 2.17 Mg per annum, shrub provided 2.69 Mg of reduction in one year in Midtown.

These results suggest that shrubs on roofs may be another option for urban planners and designers who are working to shape urban policy to mitigate air pollution with green roofs. In the case of PM_{10}, reduction, study results report that shrubs performed better than trees and grass on roofs. Shrubs, particularly evergreen species, are physiologically active all year and as such, expose more leaf surface area to gaseous air contaminants for longer periods of time compared to deciduous shrub varieties that drop their leaves in winter months. Shrubs are also lighter than trees and less invasive in their root system therefore another strong plant choice for future green roof applications in urban areas that are concerned about reducing particulate matter.

The study results also support previous studies where urban trees out-perform other forms of urban vegetation in air contaminant reduction (44). While this may be true, this researcher would suggest that green roofs with shrubs may be a better choice for urban planners and designers than urban trees in some cases. Urban trees offer many benefits when provided with dedicated space for growth and maturity, such as in parks, on recreational lands or riversides. However, urban trees in dense downtown locations are more difficult for municipalities to manage and maintain compared to installing grass or shrubs on roofs. Trees need to be carefully sited and maintained in densely populated and polluted

urban areas where grade level space is often co-opted by developers for built form. Similarly, almost 40% of newly planted urban trees succumb to heat stress, drought, air pollution or mechanical trauma in their first year (44). Also, urban trees need to be carefully permitted by municipalities so they do not interfere with overhead wires, below-ground infrastructure or the general safety of people walking on streets. Finally, trees, while aesthetically valued, take several dozen years before reaching their pinnacle in terms of air pollution mitigation. Nonetheless, as shown in the UFORE model, mature trees, compared to shrubs or grasses, possess a robust total leaf area index, and hence, expose more working leaf cells to gaseous contaminants and mitigate air pollution more profoundly than other plant species.

According to the OMA, ozone and particulate matter are two contaminants that are proven to negatively impact human health and increase costs to health care. Ozone and particulates impact humans differently depending on their age, pre-existing illness and their geography throughout Ontario. It seems that a choice to live and work in some urban areas (e.g. Toronto) for some at-risk persons is choosing to exacerbate existing health conditions due to air pollution. In the year 2000, the OMA reported that 33 million dollars worth of Ontario taxpayer's health care expenses was dedicated to treating air pollution-related phenomena (83, 84). The OMA predicts economic costs associated with air pollution using a sophisticated model called ICAP. The OMA reports that human health outcomes and the economic burdens to society associated with toxic air pollution will further deteriorate over the next decade as the population expands in concert with an insatiable reliance on burning fossil fuels for transportation, industry, heating and cooling. These predictions merge with a seeming general reluctance on the part of Provincial and Federal governments to be aggressive with strategies to reduce Ontario's air pollution and create a dismal picture of Toronto's air quality by 2015 (83, 84).

In dense urban areas where competition exists between built form and green space, pre-planned, zoned or municipally designated areas for green elements could be represented by green roofs (shrubs and grass) on elevated surfaces. Strategic use of these green roofs could be used by urban planners and designers to help meet a city's Kyoto expectations or a Provincial air quality strategy such as the Anti-Smog Action Plan in Ontario.

Application of the Study

Applications for urban green roofs are shaped by building type, load restrictions, structural capacity of the roof, age of building, municipal policies, incentives, education and awareness of building professionals, architects and roofing specialists as well as the budget and long term vision of the community of building owners in urban areas. Green roofs can be designed, positioned or aggregated to enhance certain environmental benefits as prioritized by any one particular municipality or jurisdiction. Toronto, for example, may wish to consider aggregating green roofs in certain downtown neighbourhoods in order to protect rivers and river habitats in designated sewer sheds known for their combined sewer overflows. Similarly, a municipality like Toronto may wish to prioritize green roofs within existing strategies to improve air quality, reduce urban heat island effects or enhance stormwater runoff quantity and quality, given the unsatisfactory number of beach closures and air quality advisories that are sustained in any one year. Environmental benefits from green roofs can be prioritized by policy makers and shape the amount of roof surface area devoted to greening processes in any one geographic area. Similarly, a desired environmental outcome will guide the design recommendations for a green roof by informing the depth of planting medium as well as the plant species selected for a green roof. Certain benefits such as stormwater control and building energy conservation are maximized when substrate depths exceed or are equal to 15 cm of growing medium compared with 7-10 cms.

Other environmental benefits such as air pollution mitigation and urban heat island reduction are predicted to be better served by aggregations or geographic clusters of green roofs within certain neighbourhoods. Previous studies report that ambient air temperature reductions and air quality improvements are more significant over aggregations compared with that of an individual green roof on a single building. As shown by the UFORE model in scenario 6 and 7, aggregations of green roofs clustered within the 1,216 ha Midtown neighbourhood derived significant air quality benefits from green roofs. The amalgamated City of Toronto is approximately 63,203 ha where a predicted and significant range of roof surfaces are appropriate for green roof applications (6). Using approximations one could hypothesize that targeted aggregations of green roofs would significantly improve air quality in jurisdictions with a similar size and geography at Midtown. The City of Toronto might experience significant and unprecedented reductions in ozone and particulate matter by modifying existing planning tools to include the use of green roofs on new or retrofit building projects.

'Up front' costs associated with installing green roofs may be overlooked by a developer or building owner who is eligible for public or private incentives such as density bonuses, tax savings, or energy related subsidies for green roof applications. Green roofs on condominiums for example, provide much needed access to recreational space and can act as a marketing tool for property managers to entice and retain tenants in the long term. Insurance premiums and perimeter fencing costs associated with meeting the Ontario Building Code requirements may be prohibitive to the creation of accessible (intensive) green roofs compared to inaccessible (extensive) green roofs. Nevertheless, green roof design elements can vary among green roof projects and neighbourhood buildings to influence specific or targeted environmental benefits derived from this simple and natural green technology.

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Summary

The results of this green roof study are applicable to a wide range of professionals who contribute to the creation of viable and sustainable urban communities including; urban and regional planners, watershed managers, atmospheric scientists, grass roots community leaders, parks and recreation departments, architects, landscape designers as well as urban foresters and landscape management practitioners. It is hoped that this report will spur further investigation on the effect of green roofs on air quality in other municipalities and Canadian jurisdictions as well provide support for the implementation of green roof policies that stimulate green roof installation in targeted or at-risk urban neighbourhoods. A commitment to ongoing primary green roof research will contribute to a body of slowly growing North American literature and will foster comparative studies between municipalities where different roofing membrane technologies, monitoring equipment, clusters or aggregations of green roofs, planting media and plant species have been employed. A Canadian emphasis on green roof research will contribute to the primary research required to support green roof policy development and implementation in Canadian jurisdictions particularly those with green roof research facilities.

UFORE-D reported that grass on roofs in scenarios 6 and 7 could reduce urban air contaminants such as CO, NO_2, SO_2, PM_{10}, CO_2 and ozone levels – contaminants with known deleterious health effects on human populations. Moreover, scenarios 6 and 7 were reportedly additive for air quality improvements compared with existing trees and shrubs at grade level in the urban Midtown study area. This researcher would support green roof technology as a practical and realistic planning tool for urban renewal where improvements in local air quality, ambient daytime temperatures, stormwater runoff quantity and quality, building energy performance and other benefits can be achieved with one targeted application. Green roofs make practical use of a neglected, inaccessible, urban landscape that is currently abundant within all municipalities in Canada and North America. These elevated surfaces do not require

acquisition permits or legal procurement. They are currently available for green roof assessment – particularly public buildings with government ownership. Depending on the environmental risk or municipal concern, green roofs can be aggregated and targeted within specific jurisdictions and thereby benefit neighbourhoods, communities, watersheds, air sheds as well as the constituents and natural biota therein. This researcher would offer that green roof technology is not only a viable urban air pollution mitigation strategy that can be transferred to other municipalities with equal merit but also that green roofs create a safer and more liveable space and as such, a better quality of life for urban dwellers.

CHAPTER 7: CONCLUSION

An 'ideal' urban neighbourhood might include a full range of extensive and intensive green roofs that have been planned, installed and aggregated geographically so as to maximize the environmental benefits predicted to arise from green roofs. To mitigate air pollution the green roof would incorporate a deep organic planting medium for deposition on selected and aggregated conventional flat roofs in a targeted neighbourhood. A mixture of small trees, evergreen shrubs (junipers) and native perennial grasses could be established to work synergistically and seasonally to mitigate air contaminants, even in winter months. Species recommended for green roofs are available in German publications; however, more experience and Canadian research are required to develop recommendations for the North American context. Research on green roof plant species to date reflects that irrespective of global location, plants need to be selected for drought and wind tolerance as well as hardiness to extreme temperatures in winter and summer conditions. Climate change is predicted to bring more extreme weather variations and less predictable rainfall in coming years; hence, green roofs plant species will require ongoing study across different climatic regions in Canada.

As demonstrated in the Midtown study, green roofs could be installed in urban aggregations in certain neighbourhoods, or more importantly along sewer sheds or within watershed areas. Green roofs could also be supported within a broad urban environmental policy framework or plan (as is the case in Toronto), where aggregations of green roofs in down town neighbourhoods could collectively work to reduce the volume and pollution load associated with stormwater runoff to local creeks and rivers. As well, green roofs could contribute to a specific overall urban heat island and air pollution mitigation strategy as well as a framework to meet existing Kyoto obligations. Aggregations of green roofs in targeted neighbourhoods could contribute to a collective improvement in perceived quality of life as well as the public health outcomes of long term residents.

The UFORE model has provided a strong foundation upon which to base the development of green roof policy for municipal, provincial and federal levels governments. As many jurisdictions consider the types of planning mechanisms that support low impact development and reduce urban sprawl, it is clear that prioritizing the inclusion of natural or green elements is a well-supported idea. Combining green roof technology with expansions in public transportation and green procurements that shift the burden away from burning fossil fuels is predicted significantly benefit air quality among other environmental outcomes. Similarly, further research and investment in renewable energy sources combined with strategies to improve and protect water quality, are part of the overall a necessary strategy for maintaining and creating sustainable communities. Urban planners would do well to heed the results of this report and others that strengthen the role of trees, shrubs and grasses for improving the quality of life in urban areas. As urban space is limited for tree and shrub planting, roofs now offer a reasonable habitat for the placement of vegetation that can benefit the environment and quality of life for people.

If the environmental benefits that accompany the installation of green roofs is so obvious, why then are green roofs not mandated via the building code of Ontario for every new construction both provincially and in the City of Toronto? Unfortunately green roof installation is thwarted by several barriers, not the least of which is the upfront financial costs. Green roof costs approximately twice as much as a conventional roof; therefore, it is difficult for builders and developers to rationalize this perceived economic liability (87). Similarly, there is perception that a green roof will weaken waterproofing despite there being no evidence of such as occurrence to date. Additionally, the following additional barriers tend to slow or delay the implementation of green roofs in North America:

- a dearth of experience with green roof technology among accredited professional groups who design green roof systems

- inexperience with projecting installation and maintenance costs associated with long term management of green roofs
- lack of industry standards (ASHRAE, ASTM) or guidelines and specifications in the roof sciences
- lack of qualified contractors who can install green roofs and offer warranties
- lack of incentives to make green roof applications more attractive to developers and building owners

Currently a number of green roof demonstration projects and academic research facilities are moving green roof technology forward across North America. While there are many European projects with proven environmental benefits based on specific parameters and plant species – very few publications are available in English. Many green roof researchers throughout North America are striving to make the case that the myriad of urban environmental and social benefits associated with green roofs negate the added 'up front' costs. If this financial hurdle can be gently moved aside, there could be substantive support for green roof installations across in jurisdictions in Canada, particularly Ontario, where smart growth and low impact design strategies are tantamount.

The Midtown study area was comprised by 1,216 ha within the amalgamated City of Toronto. Approximations using 10% and 20% of sampled building surfaces were grassed in order to represent green roofs and derive estimates on the effect of green roofs on air pollutant mitigation using the UFORE model. Green roofs significantly reduced air contaminants in the Midtown study area over one year. If the amalgamated City of Toronto with its 63,000 ha of land base supported a green roof policy that could target green roof applications on 5% of the available building roof surfaces, the environmental benefits, particularly on air quality and human health would be significant.

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Project Summary

Urban Forest Effects (UFORE) Model

Introduction

The Urban Forest Effects (UFORE) model is designed to use standardized field data from randomly located plots, and local hourly air pollution and meteorological data to quantify urban forest structure and numerous urban forest effects for cities across the world. The model currently quantifies:

- Urban forest structure by land use type (e.g., species composition, tree density, tree health, leaf area, leaf and tree biomass, species diversity, etc.).
- Hourly amount of pollution removed by the urban forest, and its associated percent air quality improvement throughout a year. Pollution removal is calculated for ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide and particulate matter (<10 microns).
- Hourly urban forest volatile organic compound emissions and the relative impact of tree species on net ozone and carbon monoxide formation throughout the year.
- Total carbon stored and net carbon annually sequestered by the urban forest.
- Effects of trees on building energy use and consequent effects on carbon dioxide emissions from power plants.
- Compensatory value of the forest, as well as the value of air pollution removal and carbon storage and sequestration.
- Tree pollen allergenicity index.
- Potential impact of Gypsy moth and Asian longhorned beetle infestation.
- Tree transpiration.

New UFORE components currently in development include: Human Comfort; Ultraviolet Radiation Reduction; Wildlife Habitat, Water Quality and Quantity Effects; and more Insect and Disease Potentials.

UFORE results are soon to be compatible with ArcView for display in Geographic Information Systems (GIS) that can incorporate digital cover maps to spatially display model results. Procedures for cover mapping from digital aerial photographs or satellite data have been developed.

A new UFORE Windows program will also be available for PC use in 2003. A field data collection manual has been developed along with handheld data collection programs for PDAs (e.g., Palm Pilots) to facilitate local data collection. All new model analyses have a permanent plot feature to allow for monitoring and analyzes of long-term ecosystem changes.

Cities that have been analyzed using UFORE are: Atlanta, GA; Baltimore, MD; Boston, MA; Brooklyn, NY; Calgary, Alberta; Hefei, China; Jersey City, NJ; Freehold, NJ; Moorestown, NJ; New York, NY; Ningbo, China; Philadelphia, PA; Syracuse, NY; Toronto, Ontario, and Woodbridge, NJ. Cities currently being analyzed are: Baton Rouge, LA; Houston, TX; Morgantown, WV; Phoenix, AZ; San Juan, PR, and Santiago, Chile. Many of these cities are analyzed in cooperation with local institutions.

Research Mission: Effects of Urban Forests and their Management on Human Health and Environmental Quality
USDA Forest Service, Northeastern Research Station, Syracuse, NY

Appendix 1

New UFORE management decision programs are also in development:

- UFORE Planting Locator: This GIS program will use digital cover maps and other GIS layers to map the best locations to plant trees to improve air quality and building energy conservation.
- UFORE Species Selector: Based on user inputs of planting location attributes (e.g., city, overhead restrictions) and ranking numerous trees factors (e.g., air pollution removal, low pollen emission, fall color) on scale of 0 (unimportant) to 10 (highly important), this Windows program will rank hundreds of tree species to determine the best tree to plant given the user's preferences.
- UFORE Future Effects: This GIS and Windows program will project future canopy cover and benefits of an urban forest over a 30-year period based on estimated forest growth and mortality. The program will also estimate the number of trees that need to be established annually in order to sustain or increase tree cover.

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The Urban Forest Effects (UFORE) Model:
Field Data Collection Manual

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Appendix B. Field Data Sheets

Location [ ]   Year [ ]   Plot ID: [ ]

Date [ ]   Crew [ ]   Field Land Use [ ]   Percent In [ ]   Completed: [ ]

Two Land Uses Must be Entered for Split

Split Plot [ ]   ** *If it is a split plot then two separate data sheets must be used for following categories.* **

Plot / Contact Information

Address _____   Phone Number [ ]

Resident _____   Notes: _____
_____

GPS / Photograph   GPS X [ ]   GPS Y [ ]   GPS Z [ ]   Photo # [ ]

Reference Objects

ID	Description	Direction	Distance	Notes/Comments (DBH)
1	_____	_____	_____	_____
2	_____	_____	_____	_____
3	_____	_____	_____	_____

Percent of Plot

Tree Cover [ ]   Shrub Cover [ ]   Plantable Space [ ]

Ground Covers (Percents)

Building [ ]   Cement [ ]   Tar [ ]   Other Impervious [ ]   Main. Grass [ ]   Unmain. Grass [ ]   Duff/Mulch [ ]

Bare Soil [ ]   Seedlings [ ]   Herb/Ivy [ ]   Agri. Crops [ ]   Pervious Rock [ ]   Water [ ]

Ground Covers Must Add to 100%

Shrub Data

Shrub ID	Species Code	% Shrub Area	Height	% Mass Missing	ID	Species Code	% Shrub Area	Height	% Mass Missing
1	_____	[ ]	[ ]	[ ]	6	_____	[ ]	[ ]	[ ]
2	_____	[ ]	[ ]	[ ]	7	_____	[ ]	[ ]	[ ]
3	_____	[ ]	[ ]	[ ]	8	_____	[ ]	[ ]	[ ]
4	_____	[ ]	[ ]	[ ]	9	_____	[ ]	[ ]	[ ]
5	_____	[ ]	[ ]	[ ]	10	_____	[ ]	[ ]	[ ]

Shrub Area Must Add to 100%

Notes:

_____
_____
_____

	Tree Removal rate(g/m2)	Shrub Removal Rate (g/m2)	Tree Pollution removal(Mg)	Shrub Pollution removal(Mg)	Tree Removal value ($)	Shrub Removal value ($)	Grass Removal Rate(g/m2)	Grass Removal (Mg)	Grass Removal Value ($)
CO									
BASELINE	0.25576	0.25576	0.56694	0.24584	543.69	235.77			
Green walls	0.25576	0.25576	0.063704	0	61.092	0			
No big trees	0.25576	0.25576	0.21523	0.24584	206.4	235.77			
No trees	0.25576	0.25576	0	0.25096	0	240.67			
Trees low res	0.25576	0.25576	0.56694	0.24584	543.69	235.77			
Trees off bldg	0.25576	0.25576	0.41909	0.24584	401.91	235.77			
NO2									
BASELINE	1.68884	1.73994	3.74356	1.67247	25276.5	11292.5			
Green walls	2.47137	0	0.61555	0	4156.2	0			
No big trees	1.45983	1.73994	1.22846	1.67247	8294.54	11292.5			
No trees	0	2.96231	0	2.90667	0	19625.8			
Trees low res	1.68884	1.73994	3.74356	1.67247	25276.5	11292.5			
Trees off bldg	1.66778	1.73994	2.73279	1.67247	18451.8	11292.5			
O3									
BASELINE	3.34049	3.39535	7.40468	3.26368	49996.4	22036.4			
Green walls	4.36181	0	.08641	0	7335.41	0			
No big trees	3.01846	3.39535	2.54005	3.26368	17150.4	22036.4			
No trees	0	5.09243	0	4.99677	0	33738.2			
Trees low res	3.34049	3.39535	7.40468	3.26368	49996.4	22036.4			
Trees off bldg	3.30954	3.39535	5.42293	3.26368	36615.6	22036.4			
PM10									
BASELINE	2.51057	2.80038	5.56504	2.69179	25087.2	12134.6			
Green walls	5.4957	0	1.36883	0	6170.67	0			
No big trees	2.01429	2.80038	1.69504	2.69179	7641.24	12134.6			
No trees	0	7.3028	0	7.16563	0	32302.7			
Trees low res	2.51057	2.80038	5.56504	2.69179	25087.2	12134.6			
Trees off bldg	2.47851	2.80038	4.06123	2.69179	18308	12134.6			
SO2									
BASELINE	0.62017	0.65522	1.37469	0.62981	2272.37	1041.08			
Green walls	0.91652	0	0.22828	0	377.35	0			
No big trees	0.57195	0.65522	0.4813	0.62981	795.59	1041.08			
No trees	0	1.06077	0	1.04085	0	1720.52			
Trees low res	0.62017	0.65522	1.37469	0.62981	2272.37	1041.08			
Trees off bldg	0.61834	0.65522	1.0132	0.62981	1674.82	1041.08			

Appendix 2