Energy Emissions Mitigation Using Green Roofs: Probabilistic Analysis and Integration in Market-Based Clean Air Policies

by

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Table of Contents

Dedication……………………………………………………………………………...ii
Acknowledgements iii
List of Figures vi
List of Tables viii
List of Appendices……………………………………………………………….... x
List of Abbreviations xi
List of Symbols xiii
Abstract..xvi
Chapter 1 Introduction..1
Chapter 2 Background..5
    2.1. Power Industry and Emission Control Technologies...5
    2.2. Environmental Emissions Policies...8
    2.3. The Vegetated Roof 21
    2.4. Benefits of Green Roofs..30
    2.5. Nitrogen Oxides and the Environment..40
    2.6. Modeling of Fate and Transport in Environmental Systems............................46
    2.7. Knowledge Gaps, Research Goal, and Objectives 52
Chapter 3 Methods 55
    3.1. Net Present Value Analysis...55
    3.2. Environmental Fate Fugacity-Based Model..58
    3.3. Scenario Development to Assess Policy 72
Chapter 4 A Probabilistic Economic Analysis of Green Roof Environmental Benefits...75
    4.1. Introduction 75
    4.2. Materials and Methods..78
    4.3. Results and Discussion..86
    4.4. Policy Implications 97
Chapter 5 Fugacity-based Multimedia Environmental Compartment Model 99
    5.1. Introduction 99
    5.2. Methodology...100
    5.3. Results and Discussion..113
    5.4. Integration into Economic Cost-Benefit Analysis 124
    5.5. Implications of Design and Environmental Parameters.................................130
Chapter 6 Policy Review and Analysis 132
    6.1. Presentation and Description of Results 132
    6.2. Overview of Current Green Roof Policies 132
    6.3. Regulatory Analysis..139
    6.4. Scenario Development to Assess Green Roof Policy Opportunities..............153
    6.5. Summary and Opportunities...158
Chapter 7 Conclusions and Future Directions 161

    7.1. Summary 161
    7.2. Specific Contributions of Research 162
    7.3. Future Directions 164
Appendices... 168
References.. 189

List of Figures

Figure 1.1 Global urbanization trends from 1950 to 2030 1
Figure 2.1 Sources for US electric utility net generation. 6
Figure 2.2 Emissions, sources, sinks, and regulatory strategies. 9
Figure 2.3 Traditional Scandinavian green roof in Skansen, Stockholm, Sweden 22
Figure 2.4 Components of a green roof...24
Figure 2.5 Extensive green roof at Lawrence Technological University in Southfield, Michigan 26
Figure 2.6 An intensive green roof on the Solaire Building, New York, New York........27
Figure 2.7 An example of a semi-intensive green roof in Augustenborg, Sweden 28
Figure 2.8 Distribution of rainwater in natural and built environments..........................34
Figure 2.9 Transport mechanisms between the air-soil-vegetation system. 43
Figure 2.10 General schematic of a fugacity model..49
Figure 2.11 Diagram of research path. 54
Figure 3.1 Schematic of SEDUM. Arrows represent major intermedia transport pathways incorporated in SEDUM. Not shown are the reactive losses within each compartment and advection into and out of the air compartment. 60
Figure 3.2 Transformations of reactive nitrogen species in the troposphere...................68
Figure 3.3 EPI Suite output for nitric acid...69
Figure 3.4 EPI Suite output for nitrogen oxide. 69
Figure 3.5 EPI Suite output for nitrogen dioxide. 70
Figure 4.1 Distribution of nitrogen oxide uptake per area...84
Figure 4.2 Equations used in the net present value analysis..85
Figure 4.3 Net present value over 40 years for a conventional roof and a green roof under various valuation and modeling scenarios. 91
Figure 4.4 Net present value (NPV) from 0 to year t over 40 years under (a) current methods of valuation (stormwater fees and energy savings), and (b) novel methods of valuations (stormwater fees, energy savings, and air pollution uptake)..............94
Figure 4.5 Annual environmental benefits for a 2000 m^2 green roof system in Ann Arbor, Michigan.. 96
Figure 5.1 Principal intermedia transfer terms within the air-soil-vegetation compartment system as modeled in SEDUM...108
Figure 5.2 SEDUM configuration. The model includes the air, soil, and vegetation compartments and provides information on runoff. 112
Figure 5.3 Distributions of annual uptake according to (a) experimental results and (b) SEDUM results..126
Figure 5.4 Net present value using SEDUM uptake results. 127
Figure 5.5 Net present value (NPV) from 0 to year t over 40 years under novel methods of valuation (stormwater fees, energy savings, and air pollution uptake) using SEDUM results...129

Figure A1.1 Net present value over 40 years under CO2 energy taxation policy. 169
Figure A2.1 Land use for residential, commercial, and industrial zones within the Chicago metropolitan area. 172
Figure A2.2 Landuse for residential, commercial, and industrial zones within the Detroit metropolitan area. 173
Figure A3.1: Hydrologic description of green roof system. 177
Figure A3.2: Soil moisture curves (SMCs) for green roof system. 179
Figure A3.3: Saturation profile through the green roof system. 180
Figure A3.4: Breakthrough curves for urea at z=0, the bottom of the gravel layer. 181
Figure A4.1 Estimated ozone concentration with green roofs (green) and without green roofs (blue). 185
Figure A4.2 Estimated ozone concentration with no observed urban heat island effect with green roofs (green) and without green roofs (blue). 185
Figure A4.3 Estimated aldehyde concentration with green roofs (green) and without green roofs (blue) 186
Figure A4.4 Estimated carbon monoxide concentration with green roofs (green) and without green roofs (blue). 186
Figure A4.5 Estimated formaldehyde concentration with green roofs (green) and without green roofs (blue) 187

List of Tables

Table 2.1 Goals for emissions reductions under CAA and CAIR. 10
Table 2.2 Estimated benefits of roof greening projects in Toronto and Washington, DC using the Urban Forest Effects Model 40
Table 4.1 Municipal stormwater fees per area of impervious surface. 80
Table 4.2 Roof conductance according to different energy models.................................87
Table 4.3 Net present value of roof systems under various benefit scenarios over 40-years assuming conventional roof replacement at 20 years. 92
Table 5.1 Physical chemical parameters of selected reactive nitrogen species used in SEDUM..107
Table 5.2 Intermedia Transfer (D) Values used in SEDUM. 109
Table 5.3 Concentrations and half-lives of selected reactive nitrogen species in the three environmental compartments. 110
Table 5.4 Ranges and distributions for environmental inputs. 113
Table 5.5 SEDUM results for compartment fugacities and species concentrations. 114
Table 5.6 SEDUM results for mass of species in compartments..................................115
Table 5.7 Initial screening of parameters listing those variables that alter species concentrations by more than 10%. 117
Table 5.8 Sensitivity analysis listing environmental parameters that alter fugacities, concentrations, and relevant losses by more than 10%. 118
Table 5.9 Summary of scenario parameters for Washington, DC and Toronto, Ontario 119
Table 5.10 SEDUM results for Scenario 1 once designable, measurable, and known parameters are defined. 120
Table 5.11 SEDUM results for amount of species in each compartment for Scenario 1 once designable, measurable, and known parameters are defined. 120
Table 5.12 Annual removal of reactive nitrogen species from air due to green roofs as determined by SEDUM and the UFORE Model. 122
Table 5.13 Comparison of water quality from a green roof system as determined experimentally and from SEDUM. 124
Table 5.14 Comparison of uptake estimates for experimental data and SEDUM. 125
Table 5.15 Net present value over 40 years for the conventional roof and green roof under various valuations scenarios using SEDUM results. 128
Table 6.1 Examples of direct and indirect private sector incentives.............................133
Table 6.2 Examples of command-and-control greening policies..................................136
Table 6.3 Examples of voluntary greening policies. 138
Table 6.4 Residential Stormwater Fees for Ann Arbor, Michigan 143
Table 6.5 Economic parameters for the cost benefit analysis of a 2000 m^2, one-story building in Ann Arbor, Michigan. 153

Table 6.6 Annual incentive requirement for stormwater fees for mean green roof cost competitiveness under various time horizons. 155
Table 6.7 Market price for NO_X emission allowances necessary for mean green roof cost competitiveness under various time horizons. 156
Table 6.8 Annual incentive requirements when stormwater fees and market-based emissions programs are collectively used to reduce the time horizon...................157
Table 6.9 For a green roof priced 1 standard deviation below the mean, annual incentive requirements when stormwater fees and market-based emissions programs are collectively used to reduce the time horizon...158
Table A1.1 Summary of net present value under various scenarios according to CO2 taxation energy policy..170

List of Appendices

Appendix 1 Effects of Energy Prices on the Green Roof Net Present Value.................168
Appendix 2 City Scale Economic and Environmental Benefit Analysis 171
Appendix 3 Soil Media Design: Transport Mechanisms for Nitrogenous Fertilizers.....176
Appendix 4 Incorporation of Green Roofs into Tropospheric Models 183

List of Abbreviations

AQM	Air Quality Management
AQMD	Air Quality Management District
ASTM	American Society for Testing and Materials
BACT	Best Available Control Technology
BAF	Biotope Area Factor
BMP	Best Management Practice
BVOCs	Biogenic Volatile Organic Compounds
CAA	Clean Air Act
CAAA	Clean Air Act Amendments
CAIR	Clean Air Interstate Rule
CAMR	Clean Air Mercury Rule
CCX	Chicago Climate Exchange
CEMC	Canadian Environmental Modelling Centre
CFR	Code of Federal Regulations
CO2	Carbon dioxide
CSO	Combined Sewer Overflow
CWA	Clean Water Act
DOE	Department of Energy
EP	Refers to EnergyPlus v2.0.0, building energy simulation software
EPA	Environmental Protection Agency
ERC	Emission Reduction Credit
FAB	Floor Area Bonus
FGD	flue gas desulfurization
FLL	Research Association of Landscape Development and Landscape Gardening
HNO_3	Nitric acid
HO_2NO_2	Hydroxy nitrate
HONO	Nitrous acid
IGCC	Integrated gasification combined cycle
kWh	Kilo Watt hours
LAI	Leaf area index
LTCP	Long-term control plan
MDEQ	Michigan Department of Environmental Quality
MEP	Maximum Extent Practicable
MS4	Municiple Separated Storm Sewer System
N_2O	Nitrous oxide
N_2O_5	Dinitrogen pentoxide
NAAQS	National Ambient Air Quality Standards
NBP	NO_X Budget Trading Program
NO	Nitric oxide

NO_2	Nitrogen dioxide
NO_3	Nitrate
NO_X	Nitrogen oxides
NPDES	National Pollutant Discharge Elimination System
NPV	Net Present Value
NRC	National Research Council
O_3	Ozone
OTC	Ozone Transport Commission
PAN	Peroxyacetyl nitrate
Pb	Lead
PFBC	pressurized fluidized bed combustion
PM	particulate matter
PM	Particulate matter
RECLAIM	Regional Clean Air Incentives Market
R-Value	1. Material property for insulation. 2. Refers to energy modeling using R-Value.
SCAQMD	South Coast Air Quality Management District
SCR	selective catalytic reduction
SEDUM	Sequestering Emissions: Designable Uptake Model
SIP	State Implementation Plan
SNCR	selective non-catalytic reduction
TMDL	Total Maximum Daily Load
UFORE	Urban Forest Effects
VOCs	Volatile Organic Compounds

List of Symbols

Symbol	Parameter definition	Units
a	Volumetric air content	cm^3/cm^3
A_S	Surface area	m^2
B_{EA}	Effective diffusivity in air	m^2/h
B_{EW}	Effective diffusivity in water	m^2/h
B_{MA}	Molecular diffusivity in air	m^2/h
B_{MW}	Molecular diffusivity in water	m^2/h
C_A	Concentration in air	mol/m^3
C_O	Initial uniform concentation	mol/cm^3
C^S	Solubility	mol/m^3
D_{AdvAir}	Advective transport through air	mol/Pa/h
$D_{AirSoil}$	Air to soil intermedia transfer	mol/Pa/h
$D_{AirVegetation}$	Air to vegetation intermedia transfer	mol/Pa/h
D_B	Boundary diffusion	mol/Pa/h
D_C	Cuticle diffusion	mol/Pa/h
D_{DPV}	Dry particle deposition to vegetation	mol/Pa/h
D_E	Diffusion	mol/Pa/h
D_{GDV}	Gaseous deposition to vegetation	mol/Pa/h
D_{Growth}	Growth of vegetation	mol/Pa/h
D_g^S	Diffusion coefficient of gas in soil	cm^2/s
D_h	Hydrodynamic dispersion	cm^2/s
D_L	Leachate transport from soil	mol/Pa/h
$D_{Litterfall}$	Leaf transfer from vegetation to soil	mol/Pa/h
D_l^S	Diffusion coefficient of water in soil	cm^2/s
D_{QDS}	Dry particle deposition to soil	mol/Pa/h
D_{QWS}	Wet particle deposition to soil	mol/Pa/h
D_{Runoff}	Runoff from vegetation to soil	mol/Pa/h
D_{RWS}	Rain (wet) dissolution to soil	mol/Pa/h
D_{RWV}	Rain (wet) dissolution to vegetation	mol/Pa/h
D_{RxnAir}	Reactive loss in air	mol/Pa/h
$D_{RxnSoil}$	Reactive loss in soil	mol/Pa/h
$D_{RxnVegetation}$	Reactive loss in vegetation	mol/Pa/h

$D_{SoilAir}$	Soil to air intermedia transfer	mol/Pa/h
$D_{SoilVegetation}$	Soil to vegetation intermedia transfer	mol/Pa/h
$D_{VegetationAir}$	Vegetation to air intermedia transfer	mol/Pa/h
$D_{VegetationSoil}$	Vegetation to soil intermedia transfer	mol/Pa/h
D_{WPV}	Wet particle deposition to vegetation	mol/Pa/h
E_A	Emission to air	mol/h
f_{Air}	Fugacity in air	Pa
FrUF	Fraction of rain intercepted by vegetation	--
f_{Soil}	Fugacity in soil	Pa
$f_{Vegetation}$	Fugacity in vegetation	Pa
G_{Air}	Volumetric flow rate of air	m^3/h
H	Henry's constant	Pa m^3/mol
k_{Air}	Reaction rate in air	1/h
K_{AW}	Air-water partition coefficient	--
K_d	Distribution coefficient in a linear isotherm	--
k_{EA}	Air side mass transfer coefficient	m/h
K_H	Henry’s constant	cmH_2O cm^3/mol
K_{OA}	Octanol-air partition coefficient	--
K_{OC}	Organic carbon partition coefficient	--
K_{OW}	Octanol-water partition coefficient	--
K_{QA}	Aerosol-air partition coefficient	--
k_{Soil}	Reaction rate in soil	1/h
$k_{Vegetation}$	Reaction rate in vegetation	1/h
L	Leaf area index	m^2_{leaf} / m^2_{land}
n	Porosity	$m^3_{void}/m^3_{total\ soil}$
P_C	Cuticle permeance	m/s
P^S	Partial pressure	Pa
Q	Scavenging ratio	--
q	Progression rate	cm/s
Θ	Volumetric water content	cm^3/cm^3
R	Ideal gas constant	Pa m^3/mol/K
ρ_b	Soil bulk density	kg/cm^3
R_d	Retardation coefficient due to sorption	--
ρ_Q	aerosol density	kg/m^3
ρ_S	soil density	kg/m^3
$R_{TAdvAir}$	Relative ratio in advective transport through air	--
$R_{TAirSoil}$	Relative ratio in air to soil intermedia transfer	--
$R_{TAirVegetation}$	Relative ratio air to vegetation intermedia transfer	--

R_{TL}	Relative ratio leachate transport from soil	--
$R_{TRxnAir}$	Relative ratio reactive loss in air	--
$R_{TRxnSoil}$	Relative ratio reactive loss in soil	--
$R_{TRxnVegetation}$	Relative ratio reactive loss in vegetation	--
$R_{TSoilAir}$	Relative ratio soil to air intermedia transfer	--
$R_{TSoilVegetation}$	Relative ratio soil to vegetation intermedia transfer	--
$R_{TVegetationAir}$	Relative ratio vegetation to air intermedia transfer	--
$R_{TVegetationSoil}$	Relative ratio vegetation to soil intermedia transfer	--
T	Temperature	K
t	Time	s
Tr	Transpiration rate	$m^3_{water}/m^2_{area}/h$
TSCF	Transpiration stream concentration factor	$m^3_{water}/m^3_{xylem\ sap}$
U_B	Mass transfer coefficient air boundary	m/h
U_C	Mass transfer coefficient cuticle	m/h
U_Q	Dry deposition velocity	m/h
U_R	Rain rate	$m^3_{rain}/m^2_{area}/h$
v_A	Volume fraction air in soil	m^3_{air}/m^3_{soil}
V_{Air}	Volume of air compartment	m^3
v_{FO}	Volume fraction octanol-like in vegetation	$m^3_{octanol\text{-}like}/m^3_{vegetation}$
v_Q	Volume fraction aerosols	$m^3_{aerosols}/m^3_{air}$
V_{Soil}	Volume of soil compartment	m^3
$V_{Vegetation}$	Volume of vegetation compartment	m^3
v_W	Volume fraction water in soil	m^3_{water}/m^3_{soil}
x	Position	cm
y_{OC}	Mass fraction organic carbon	$kg_{organic\ carbon}/kg_{soil}$
y_{OM}	Mass fraction organic matter	$kg_{org\ carbon}/kg_{aerosol}$
Y_S	Diffusion path length in soil	m
$Z_{Aerosol}$	Fugacity capacity in aerosol	$mol/Pa/m^3$
Z_{Air}	Fugacity capacity in air	$mol/Pa/m^3$
Z_{Air}	Fugacity capacity in air	$mol/Pa/m^3$
$Z_{Octanol}$	Fugacity capacity in octanol	$mol/Pa/m^3$
Z_{Soil}	Fugacity capacity in soil	$mol/Pa/m^3$
Z_{Water}	Fugacity capacity in water	$mol/Pa/m^3$

Abstract

Our urban infrastructure systems are stressed. The decay of water infrastructure is spurring demand for innovative solutions for stormwater management. Concurrently, the transition of predominantly coal-based utilities to renewable portfolios is slow, resulting in continuing adverse health impacts from air pollution. The need for emissions management and resilient water infrastructure in cities will further increase as the world's population continues to move to urban centers.

This dissertation explores the technical, economic, and policy opportunities for vegetated roofs as one solution to stormwater and energy emissions management. The objective was to explore policy strategies to integrate green roofs into emissions management using quantitative economic and physical-chemical modeling tools.

A net present value (NPV) approach was used to compare the cost of a conventional roof to a green roof accounting for benefits for stormwater, air pollution, and building energy conservation. Results indicated that, while a green roof costs 39 percent more initially, the 40-year NPV is 23 to 30 percent less mainly due to energy savings and potential health benefits from air pollution reduction. The impact of stormwater fees was minimal.

The benefit of green roofs to improve air quality is novel, and had to date not been explored quantitatively. A probabilistic, fugacity-based fate and transport model, SEDUM (Sequestering Emissions: Designable Uptake Model), was developed to assess the uptake of reactive nitrogen species (NO_2, NO, and HNO_3). The model estimates uptake by vegetation and soil media, which were compared with dry deposition model results and water quality data. Under polluted conditions, a mean removal rate of 0.20 ± 0.01 $kgNO_2/m^2/y$ was estimated using SEDUM. For a 2,000 m^2 roof, this translates into a health benefit between $640 and $2426 per year. Design parameters that impact pollutant uptake were identified.

Analysis of current stormwater and air quality policies showed that market-based incentives can close the cost differential once both stormwater and air quality incentives are considered. This work was sufficiently robust to demonstrate the economic and emissions mitigation potential to be included in best available control technology (BACT) consideration. Yet, market-based policy incentives are currently insufficient for widespread adoption.

Chapter 1

Introduction

The American Society of Civil Engineers' 2005 *Report Card for America's Infrastructure* assessed 12 categories for the Nation’s infrastructure and gave it a grade point average of D. Congested highways, overflowing sewers and corroding bridges are constant reminders of the looming crisis that jeopardizes our nation's prosperity and our quality of life. At a total estimated infrastructure rehabilitation cost of $1.6 trillion for the next 5 years, this need (in the US alone) comes at a time of increased urbanization (and thus demand on infrastructure) nationally and globally.

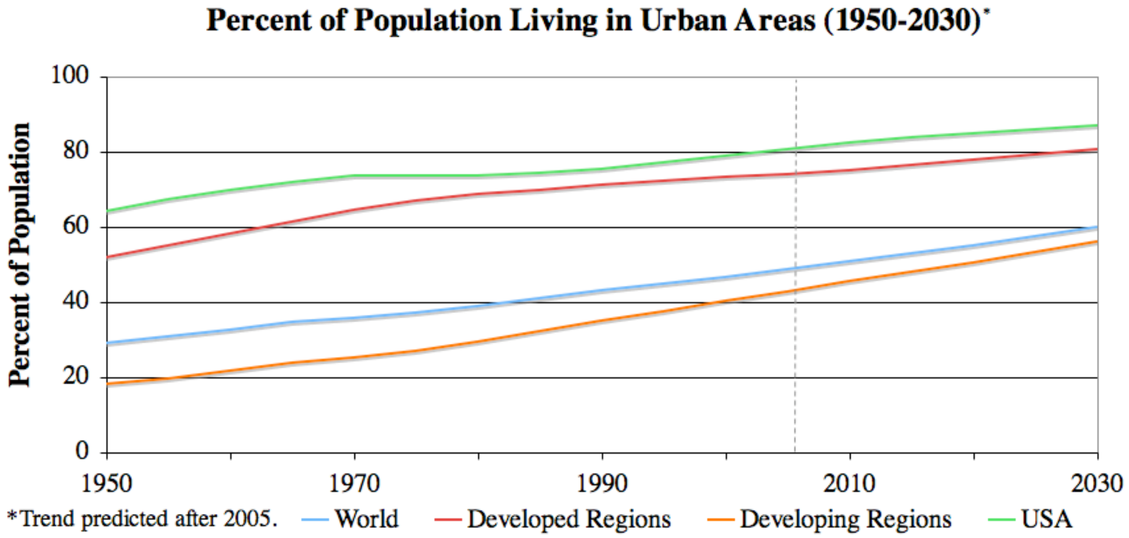


Figure 1.1 Global urbanization trends from 1950 to 2030 (adapted from UN ESA, 2006).

By 2010, it is predicted that the majority of the world’s population will live in urban areas (UN ESA, 2006). In more developed regions, the percentage of the population that lives in urbanized areas will exceed seventy-five percent by 2010 and reach eighty percent by 2030 (UN ESA, 2006). Figure 1.1 shows the increasing urbanization population trend. Between 1900 and 2000, there was more than a twentyfold increase in the number of cities with populations exceeding one million persons (McGranahan et al., 2005). Between 2005 and 2030 it is estimated that the world's urban population will increase from 3.2 billion to 4.9 billion (UN ESA, 2006).

The resulting growth and horizontal expansion of cities will stress private and public utilities. Growth creates a demand for energy, water and sewer services, and transportation; meeting this demand has impacts both globally and locally. To meet the increased energy demand between 2003 and 2025, the US has proposed more than 150 new coal-fired power plants (Bradsher and Barboza, 2006). During the same period, China has proposed over 600 new coal-fired power plants leading China to contribute to 40% of global carbon dioxide emissions by 2024 (Bradsher and Barboza, 2006).

At the same time, the conversion of green space into residential developments, shopping malls, and other built infrastructure impacts storm sewer systems because areas previously involved in water infiltration and aquifer recharge are replaced with impervious surfaces that export runoff (US EPA, 2005). The need for new sewer construction in southeast Michigan is estimated to total 42% of the estimated $14 to $26 billion needed for long-term stormwater management through 2030 (SEMCOG, 2001). In addition to impacting storm sewers, new road infrastructure leads to increased vehicle emissions, and along with parking lots and rooftops, roads contribute to elevated urban surface temperatures by reducing a city's albedo. Increased temperatures in combination with anthropogenic emissions including those from the electric utility industry impact local urban air as well as regional air quality.

To address the infrastructure woes and temper the environmental impacts of growing cities, city planners and developers are seeking multi-faceted, scalable and cost-effective solutions.. Increasingly, industries and governments are recognizing that green (vegetated) roofs may be part of the solution. Witness the increased adoption or consideration of the technology in Germany and Canada, and more recently in cities in the Pacific Northwest, Chicago, and Washington, DC, as well as implementation in industrial facilities (Ford, Alcoa, Daimler-Chrysler, and others).

Despite being touted for their mitigation of stormwater volume runoff, and heating/cooling benefits, one challenge facing widespread integration of green roofs are their premium cost over conventional roofs, and the lack of verifiable quantitative data on their varied benefits. While other countries have succeeded in encouraging the technology through a command-and-control approach for stormwater management, the internal rate of return on the investment is poorly quantified and highly dependent on local assumptions and negotiations. Results indicate that there is an opportunity for integrating the technology for air pollution mitigation, provided this public benefit can be transferred to the building owner through financial incentives or integration into market-based emissions management policies.

Central to this new framework is the need for a rigorous quantification of the benefits of green roofs as an air pollution mitigation tool, to inform policy design and identify opportunities in existing air policies. This dissertation will explore the economic opportunity for air quality management through green roofs within the context of all other quantifiable benefits through a meta-analysis of currently available data (Objective 1). Economic opportunity is evaluated at the individual building scale. To translate public benefits to the private sector, the extent of air pollution mitigation by green roofs must be understood. To this end, rigorous probabilistic tools are needed to quantify the fate and transport of electric utility pollutants (the industry currently trading emission allowances in the US) in green roof systems (Objective 2). Finally, the current state of green roof policy and US air emissions policy needs to be surveyed to assess the opportunity for scientifically-informed and economically advantageous integration of green roofs in air emissions mitigation policies (Objective 3).

Chapter 2

Background

This section summarizes the relevant literature pertaining to electric utility emissions, quantification of the air pollution mitigating capability of green roof systems, and the potential for integration into various emission policy scenarios.

2.1. Power Industry and Emission Control Technologies

In the United States, the electric power industry includes all power producers, consisting of both regulated utilities and non-utilities (e.g. independent power producers, qualifying cogenerators, and other small power producers). While utilities primarily generate power for the US electric grid for sale to retail customers, non-utilities produce electricity for their own use, to sell to large consumers, or to sell on the wholesale electricity market (e.g. to utilities for distribution and resale to customers). The US electric power industry has undergone significant changes as both federal and state government agencies have modified regulations to create a more competitive market for electricity generation. As a result, non-utility power producers have increased and bought generating capacity from electric utilities.

Coal-fired power plants are the predominant type (approximately 50%) of power generation in the United States (see Figure 2.1).

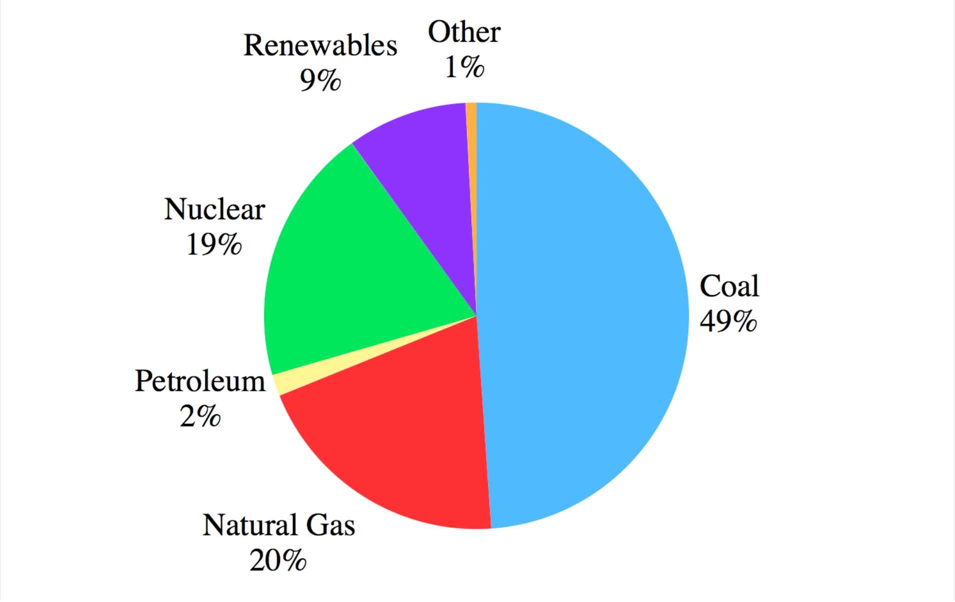


Figure 2.1 Sources for US electric utility net generation (US DOE, 2007).

US electric utility sales were 4,055 billion kWh in 2005 (US DOE, 2007). Coal-fired electricity generation accounted for 2,013 billion kWh, or 49.7% of total generation (US DOE, 2007). Coal generation grew by 1.7% over 2004 although the share of coal in total net generation has declined from 52.1% in 1994 (US DOE, 2007).

Atmospheric emissions from electric power utilities are linked with the generation of acid rain (from SO_2 emission), exposure to fine particulates (those less than 10 micrometers in diameter), smog, regional haze, and global climate change (US EPA, 2004). The power industry is a significant source of sulfur dioxide (SO_2), nitrogen oxides (NO_X), and mercury. It is still responsible for approximately 70% of SO_2, 20% of NO_X, and 40% of mercury emitted into the environment (US EPA, 2004). These emissions contribute to human health problems within production areas and outside the region due to the long-range transport of pollutants.

Under the Clean Air Act (CAA), stationary sources such as electricity-generating facilities are defined as single sources with emissions exceeding a threshold level that depends on the pollutant. This threshold is generally 100 tons per year for criteria pollutants and their precursors; however, the threshold for lead is 5 tons per year (40 CFR 52.21). For the most severe ozone (O_3) non-attainment areas, the threshold for volatile organic compounds (VOCs) can be as low as 10 tons per year. For serious carbon monoxide (CO) non-attainment areas, the CO threshold is 50 tons per year (40 CFR 52.21).

Abatement of pollutant emissions from coal combustion flue gas through technologies must meet local, state, and federal regulations. The trend in these regulations is to tighten requirements for new sources of pollution as well as to require retrofit of existing power generating equipment with environmental controls. The modern power plant is typically equipped with a high efficiency fabric filter ('baghouse') or electrostatic precipitators (ESP) for particulate removal, staged combustion burner configurations for low-NO_X emissions, and post-combustion flue gas treatment devices for NO_X and SO_2 control (US DOE, 2007). Examples of the latter devices are selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) technologies for NO_X control and high efficiency flue gas desulfurization (FGD) scrubbers for SO_2 control. For SCRs and SNCRs with low NO_X burners, emissions can be reduced by 70 to 90 percent (US DOE, 2007).

Additionally, advanced coal-fired power generation technologies are evolving from cooperative efforts between the US Department of Energy and industry, such as those being demonstrated in the Clean Coal Technology Program. Technologies such as integrated gasification combined cycle (IGCC) and pressurized fluidized bed combustion (PFBC) are capable of producing electricity more efficiently than a conventional pulverized coal combustion power plant. These advanced power systems are also equipped with very high efficiency gas cleanup technologies.

In practice, many of the existing coal-fired power generation facilities do not contain modern flue gas treatment systems. In 2005, the coal-fired power generating capacity equipped with scrubbing technology represented 32% of the total coal-fired capacity (101.6 GW) (US DOE, 2007). Much of the remaining capacity meets regulatory requirements for SO_2 emissions through fuel switching, either to lower sulfur coal or by co-firing low sulfur fuels such as natural gas or biomass (US DOE, 2007). Similarly, control of NO_X emissions is primarily accomplished with low-NO_X burners (LNB), which are cheaper than SCR or SNCR, but do not offer the same emission reductions. To address these concerns, policies are evolving to help reduce emissions from electricity production through regulatory or voluntary implementation of technologies.

2.2. Environmental Emissions Policies

The previous section detailed current strategies for controlling point-source emissions. Air emissions are generally regulated at the source. Sinks, reservoirs that receive or remove pollution, play a role in air quality and pollutant management especially for CO_s management. This section will summarize the approaches to environmental emission policies focusing on those pertaining to US electricity generators and nitrogen oxides. This is briefly summarized in Figure 2.2.

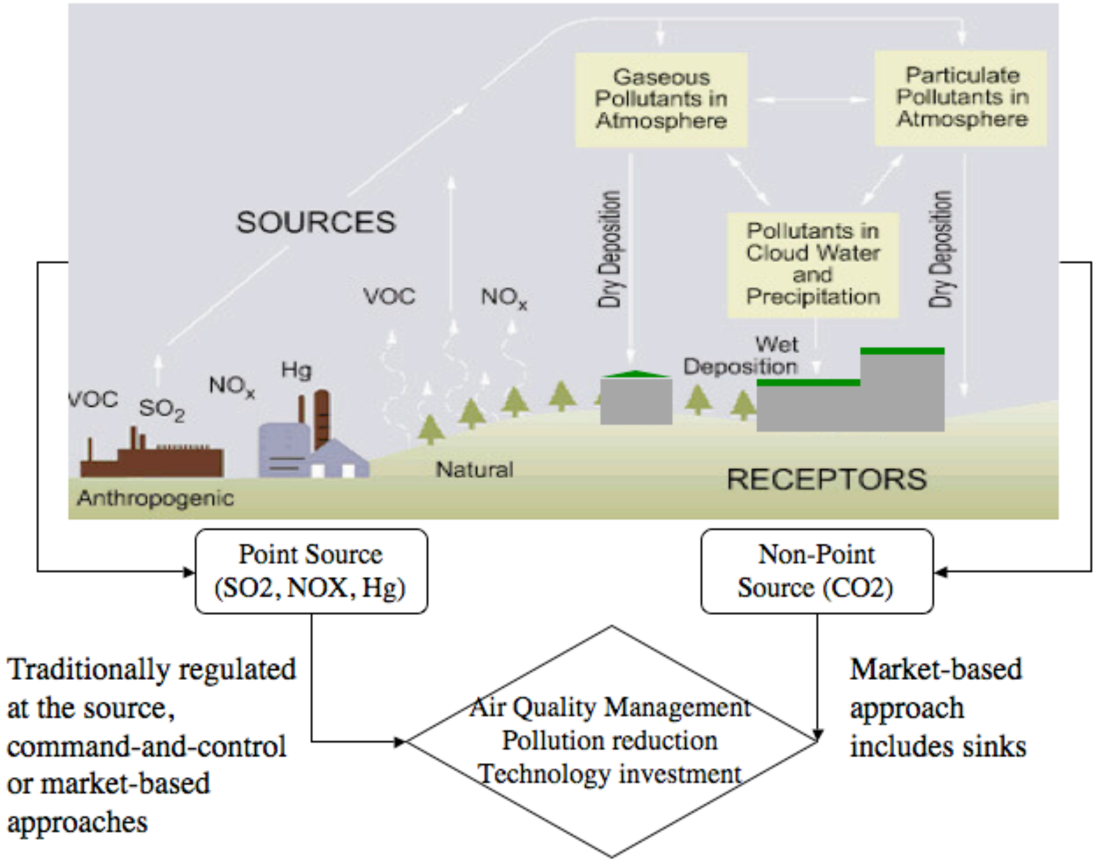


Figure 2.2 Emissions, sources, sinks, and regulatory strategies (modified from NY DEC, 2003).

The Clean Air Act (CAA) provides the legal framework for (i) mitigating potentially harmful ambient concentrations of six "criteria" pollutants, which include carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ozone (O_3), particulate matter (PM), and lead (Pb); and (ii) reducing emissions of substances that cause acid deposition, specifically sulfur dioxide and nitrogen oxides (NO_X). The implementation of the CAA has contributed to substantial decreases in emissions of several pollutants, including via programs for stationary sources such as the power generating industry. However, most of the reductions have been accomplished through regulations on new facilities, while many older, often higher-emitting facilities can be a substantial source of emissions.

In March 2005, the US Environmental Protection Agency issued the Clean Air Interstate Rule (CAIR) to target reductions of sulfur dioxide and nitrogen oxide emissions. CAIR achieves large reductions of SO_2 and NO_X emissions across 28 eastern states and the District of Columbia. When fully implemented, CAIR will reduce SO_2 emissions in these states by over 70 percent (by 3.6 million tons in 2010 and 3.9 million tons in 2015) and NO_X emissions by over 60 percent from 2003 levels (1.2 million tons in 2009 and 1.5 million tons in 2015). It is expected to provide $85 to $100 billion in health benefits and nearly $2 billion in visibility benefits per year by 2015 (US EPA, 2005)

Table 2.1 Goals for emissions reductions under CAA and CAIR.

Program	**Nitrogen Oxides (NOx)**	**Sulfur Dioxide (SO_2)**	**Mercury (Hg)**
Clean Air Act (Existing)	1.25 million ton cap by 2010	2 million ton cap by 2012	5 tons per year by 2008
Clear Skies Initiative (two-step approach)	**1st Step** 2.1 million ton cap by 2008	**1st Step** 4.5 million ton cap by 2010	**1st Step** 26 tons per year by 2010
	Optional 2nd Step 1.7 million ton cap by 2018	**Optional 2nd Step** 3 million ton cap by 2018	**Optional 2nd Step** 15 tons per year by 2018

Traditionally, stationary sources (see Figure 2.2) have been regulated through the imposition of emission standards or limitations. The CAA defines such a standard or limitation “as a requirement established by the State or the Administrator which limits the quantity, rate, or concentration of emissions of a source to assure continuous emission reduction, and any design, equipment, work practice or operational standard promulgated under this Act.” Although many specific programs regulate stationary sources in the CAA, the basic approaches that have been adopted to achieve emission reductions fall into three broad categories: technology specification standards (or design standards), performance standards, and the newer use of cap-and-trade requirements (NRC, 2004).

A *design standard* mandates that a set of design or technological options (for example, installation of particle traps in smoke stacks) must be adopted by regulated facilities to meet emission targets. Although this approach has the potential to achieve substantial reductions in air emissions, it is criticized as being overly inflexible and cost-ineffective. For example, while there is often a substantial disparity in the marginal costs of emission reductions among facilities affected by the same technology standard. Technology-specification standards do not allow market forces to use this disparity to minimize the overall costs of the desired level of emission reductions (Hahn and Stavins, 1992; Stavins, 2000). Moreover, because firms must use the technologies specified in the standard, the approach does not encourage individual firms to pursue ways to reduce emissions through potentially more effective alternative technologies and front-end process adjustments.

In contrast to a design standard, a *performance standard* specifies a maximum allowable rate of emission from a given type of source or facility, and the managers of the facility may choose any combination of technologies and operational practices to meet the standard. In principle, this approach provides an individual facility with greater flexibility to discover the most cost-effective way to meet the emission standard. Although the flexibility exists in theory, in practice the performance standard is normally set at the level that can only most readily be achieved by a known technology. Thus, unless readily available alternatives can meet the standards to the satisfaction of the regulators, there is likely to be a tendency for facilities to default to the known technology.

The performance standard can set various degrees of control for different sources—low-emission sources may have a lower control requirement than high-emission sources. However, regulators faced with setting a performance standard often compromise, setting a standard at a lower level than the one that can be achieved by many facilities so that the facility with the largest uncontrolled emissions will not face an economically debilitating task of control. As a result, marginal costs of emission reductions often continue to vary substantially among facilities. Further, once a performance standard is achieved at a facility, there is little incentive to implement more efficient ways of achieving the same or greater emission reduction, and, most important, there is no mechanism for a company to profit from innovations that achieve emission reductions beyond the standard.

The choice between a design and a performance standard is often made as part of a rule-making process. In some cases, such as fugitive emissions, those emissions not captured by control technologies and are often a result of equipment leaks, it is simpler to set a design standard because of the complexity of measuring the actual emissions. However, design standards do not provide the same limit on emissions that performance standards do; they simply provide a reduction over a set of baseline emissions. In either case, the standards are related to the output of the facility. Performance standards are usually expressed in such terms as pounds of pollutant emitted per million British thermal units (Btu) of fuel heat input. In these cases, the actual amount of emissions is permitted to increase as the amount of fuel is increased.

2.2.1. Market-based Instruments

Market-based instruments are defined according to the following:

> *"To address the market failure of 'environmental externalities' either by incorporating the external cost of production or consumption activities through taxes or charges on processes or products, or by creating property rights and facilitating the establishment of a proxy market for the use of environmental services*" (EEA, 2007).

Four major categories of market-based instruments exist: pollution fees, government subsidies, market barrier reductions, and tradable permits. This section summarizes the four categories and provides examples from US air emissions policy.

Pollution fees and government subsidies approach the problem from opposite sides. Pollution fees or charges assign a tax on the amount of pollution generated by a firm. Fees encourage the firm to reduce emissions until the marginal abatement cost is equal to the tax (Stavins, 2000). Set appropriately, the fee is a Pigouvian tax named after A.G. Pigou, who argued in 1920 that when facing an externality such as pollution, the appropriate remedy is to impose a per unit tax on the emissions from a polluting activity (Pigou, 1920). A tax rate equal to the marginal external social damage causes firms to internalize the externality, pollution (Kolstad, 1999). Firms control pollution to varying degrees depending upon the cost of control with low-cost controllers reducing pollution more than high-cost controllers.

Government subsidy reductions also provide incentives to address environmental problems. Instead of a tax on the amount of pollution generated, a firm is rewarded through a reduction in fees for reducing pollution generation. In practice, incentives may promote economically inefficient and environmentally unsound practices if they are not well-implemented. The challenge with pollution fees and incentives is establishing the appropriate level of tax (or tax relief) to achieve the optimal level of pollution control.

Insufficient taxation per unit pollution provides no incentive to decrease emissions resulting in increasing ecological damage. Over-taxation results in above desired results of pollution abatement but at great expense to firms. (Costanza et al., 1997). When a tax per unit pollution is set to the optimal amount, the quantity a facility emits is equal to the amount where the marginal environmental damage function intersects with the marginal treatment cost function (Costanza et al., 1997).

Market-barrier reductions can increase gains in environmental protection by removing explicit or implicit barriers to market activity, thereby reducing transaction costs. Removal of barriers can occur by creating markets (e.g. CO_2 emissions trading), developing or altering liability rules, and creating information programs about technologies (e.g. EnergyStar label for efficient appliances).

In the *tradable permits approach*, each source category (or every source) in a given geographic area has its total emissions of a particular pollutant capped at a level below its current level, and each individual source is assigned an emissions allotment consistent in the aggregate with the overall emissions cap. The novel aspects of this total-emissions-based performance standard are the following:

(1) It does not presume any particular technology or emissions standard for the sources; and

(2) It allows market forces to minimize costs and reward innovation (Tietenberg, 2005).

Each facility is allowed to achieve the required reductions in a variety of ways, including conventional pollution control, process change, and product substitution, as well as purchase of reductions at a more economical rate from other facilities that have exceeded their reduction target. Sources that reduce emissions below their allotted level can sell their surplus allowances to other firms to offset excess emissions (Swift and Mazurek, 2001). The firms that find emissions control more costly purchase the allowances creating continuous incentives for firms to find cheaper, cleaner technologies.

With a cap-and-trade standard, an emission limit must be set that is also based on feasible control technology or process operations. However, the ability to trade removes one of the problems faced by regulators when dealing with a range of existing sources. A greater control requirement can be set, and companies that cannot easily meet the requirement can trade emission-reduction credits to comply with the cap-and-trade requirement. There are challenges in applying this emission-control mechanism in every situation, but the mechanism does, at least in theory, offer the possibility of achieving substantial reductions while allowing individual sources to minimize costs and optimize efficiency.

2.2.2. Market-based Instruments in US Air Policy

This section summarizes the US experience with air emission tradable permits (sulfur dioxide and nitrogen oxide programs) and possible future directions for emission trade policies.

The US has utilized market-based instruments to incentivise stationary sources (see Figure 2.2) to implement emissions reduction strategies. For example, the EPA estimates that emissions of the six criteria pollutants have decreased by about 30% over the past three decades, despite sizable increases in population, energy use, and gross domestic product. The estimated benefits of these reductions are substantial; they include an estimated 100,000 to 300,000 fewer premature deaths per year and 30,000 to 60,000 fewer children each year with IQs below 70 (US EPA, 1997). Economic assessments of the overall costs and benefits of air quality management in the United States indicate, despite uncertainties, that implementation of the CAA has had and will probably continue to have substantial net economic benefits. For a more in-depth discussion of CAA implementation programs, see the National Research Council's review of air quality management (AQM) in the US (NRC, 2004).

Sulfur Dioxide Trading Program

In 1989, the G.H.W Bush administration proposed an emissions reduction system, to reduce sulfur dioxide emissions that were contributing to acid rain (Swift and Mazurek, 2001). The Acid Rain Program, covered in Title IV of the 1990 Clean Air Act Amendments (CAAA), established a national "cap" on the total amount of emissions of SO_2 from utilities. Those utilities that could reduce emissions cheaply could sell the unused allowances to utilities where emission abatement would be more costly.

EPA issues 8.95 million tons of SO_2 allowances to covered sources annually, which is approximately 10 million tons less than the amount of SO_2 emissions by utilities in 1980 (Burtraw et al., 2005). The reduction to 8.95 million tons occurred through a two-phase introduction. In 1995, Phase 1 targeted the 110 largest SO_2 emitters within coal-fired electricity generators. In 2000, the remaining coal-fired electricity generators that produce more than 25 megawatts or have high sulfur content in their coal were included in Phase 2 (Burtraw et al., 2005). Sources may trade allowances, but each source must hold an allowance for each ton of SO_2 emitted that year. If annual SO_2 emissions exceed the number of allowances held at the end of the year, firms are required to pay penalties of $2,000 based on an annual adjustment factor for each ton exceeded (EPA 1997). Once an allowance is used, it is retired. However, for any allowances that are not used during a year, the allowance may be used or sold in subsequent years. This cap-and-trade system has been estimated to cost firms approximately $1 billion while a rate-based approach to control SO_2 would have cost companies $4.5 billion to achieve similar results (Swift and Mazurek, 2001).

Nitrogen Oxide Trading Programs

Nitrogen Oxide (NO_X) emissions are regulated under Title IV (Acid Rain Program) and Title 1 (National Ambient Air Quality Standards, NAAQS) of the CAAA. Several programs have been introduced to reduce NOx emissions to assist in meeting the NAAQS for ozone.

The first urban area emission trade program began in the Los Angeles basin in 1994. The **Regional Clean Air Incentives Market (RECLAIM)** initiated by the South Coast Air Quality Management District originally included SO_2 and VOCs in addition to NOx emissions trading (Burtraw et al., 2005). While the Acid Rain Program was successful in implementing banking allowances for future years, the RECLAIM Program does not formally permit banking. There is an informal temporal trading that can occur as allowances are allotted annually on two cycles from July to June and from January to December, and trading can occur between the cycles for a particular year. Aggregate NO_X emissions from participants were approximately twenty percent below allocations in 2003 (Wallerstein et al., 2005). Between 1994 and 2003, annual NO_X emissions for RECLAIM participants decreased from 25,314 tons to 9,942 tons.

While the Los Angeles basin struggles to meet NAAQS for ozone due to the inversion layer that frequently occurs when a warmer air mass is confined by the surrounding mountains, long-range transport of nitrogen oxides can lead to ozone non-attainment for areas downwind of emission sources. To address this phenomenon, the Ozone Transport Commission (OTC) was formed to develop NOx and VOC emission standards to address ozone attainment in the northeast corridor of the US. Congress created the commission with the 1990 CAAA, and in 1994, the states agreed to implement a trade program for large source emitters. The OTC NOx Budget Program began in 1999 and regulates emissions from May 1 through September 30 (Burtraw et al., 2005). The program established three geographic zones with different levels of achievement standards for the three zones to be implemented in phase two with mixed results. While NO_X emissions within the budget program decreased during the ozone season by 60 percent (nearly 280,000 tons) between 1990 and 2002, ozone levels remained relatively constant during the same period (US EPA, 2003). As many populated areas in the northeast corridor remained in non-attainment of the NAAQS standards for 1-hour ozone levels (120 ppb) and 8-hour levels (80 ppb), the program was replaced with the NOx SIP (State Implementation Plan) Call Program in 2003 (US EPA, 2003).

The **NO_X SIP Call Program** expanded the number of states involved to achieve reductions from upwind states employing 126 of Title 1 to petition the EPA administrator for reductions. Originally, this program targeted 22 states accounting for 90% of boilers covered in the Title IV program, but currently has 19 states participating. Regionally, this program expects to reduce 2007 emissions by 34% from a baseline of 3.51 million tons and summertime emissions by 62% from a baseline of 1.5 million tons. These reductions will reduce national emissions by 22% of the 5.4 million ton baseline in 2007 and summertime emissions by 40% of 2.4 million tons in 2007 (Burtraw et al., 2005).

Future Policies: Mercury and Carbon

In March 2005, EPA issued the Clean Air Mercury Rule (CAMR) limiting mercury emissions from new and existing coal-fired power plants by creating a market-based cap-and-trade program. The program will cap mercury emissions in two phases: the first phase cap is 38 tons beginning in 2010, with a final cap set at 15 tons beginning in 2018 (US EPA, 2005). Mercury is a hazardous air pollutant, and this is the first such pollutant in the US to be controlled via a market-based approach. Traditionally, EPA has chosen a command-and-control approach to regulating such pollutants except in the phase-out period of lead from gasoline (Stavins, 2000).

Swift and Mazurek (2001) argue that it is critical to include carbon in an emissions reduction policy as utilities face two different choices in deciding how to reduce NO_X, SO_2, and mercury emissions. Without carbon in the emissions reduction policy, the current path toward compliance is to install end-of-pipe controls on existing coal-fired power plants. By incorporating carbon into the policy, there is an incentive to invest in clean power technologies, including clean coal technologies.

With the ratification of the Kyoto Protocol by 155 states and regional economic integration organizations as of August 31, 2005, carbon trading is gaining acceptance as a means of meeting the objectives of the protocol (UNFCCC, 2005). Those that signed the protocol are committed to reducing carbon dioxide equivalent emissions to at least 5 percent below the country's emissions in 1990 (UNFCCC, 1997). Countries within the European Union have begun trading carbon and voluntary carbon trades within the US occur within the Chicago Climate Exchange (CCX) (CCX, 2005). Total trading volume in 2006 on the CCX was approximately 10.3 million tons of carbon dioxide (CCX, 2007).

The CCX is the only carbon allowance market that trades carbon sequestration credits, including urban tree planting and agricultural soil sequestration. In 2006, more than 4 million metric tons of allowances were issued for offset activities (CCX, 2007).

As the international pressure for controlling carbon emissions increases, more programs are developing within the US. Recently, nine northeastern states came to a preliminary agreement to freeze carbon-based electric utility emissions at current levels and reduce them by ten percent by 2020 (DePalma, 2005). Trading is expected to begin on January 1, 2009 and will only involve large firms in the electric generating sector (Kirkman, 2006). While the federal government has refused to ratify the Kyoto Protocol, trading of carbon emissions is being implemented at the local and regional level within the US.

Limitations of Emissions Trading and Challenges for Air Quality Management

The primary environmental concern with emissions trading is the generation of “hot spots,” locations of increased and concentrated emissions. Although hot spots did not develop under the sulfur dioxide program, setting pre-program baselines is one method to ensure that areas do not experience increases in emissions.

Several challenges posed by the NRC for future improvements in air quality are relevant to the research in this dissertation because of their connections between the private and public sectors. Pollutants such as O_3, $PM_{2.5}$, and regional haze share, to some extent, common precursor emissions and chemical pathways are all to greater or lesser extents affected by long-range transport. <u>A multi-pollutant, multi-state approach should minimize the possibility that control strategies implemented for one pollutant will inadvertently increase the concentrations of another pollutant</u> and should enhance the ability of policymakers to maximize the cost-effectiveness of their overall air pollution control strategies.

The goal of protecting ecosystems is clearly enunciated in the CAA. The protection and maintenance of ecosystems is critical because ecosystems provide invaluable services (e.g. water purification, water supply, forest production, and carbon and nitrogen fixation) that are essential to our economy and public health. As protection of the air and water-based ecosystems intersect legislatively, there is an opportunity to develop and implement ‘dual use’ technologies.

The primary emphasis of air quality management in the United States has been on controlling emissions in and nearby urban and industrial centers where pollutant concentrations are generally the highest. This approach is often referred to as a local pollution control strategy. During the late 1980s and 1990s, it was realized that controlling local emissions alone was insufficient to meet the air quality standards for some air pollutants in some areas. In response, regional planning organizations were created to devise multi-state strategies and, hence, scaling of the approaches to control emissions becomes a dominant concern and area of uncertainty.

2.3. The Vegetated Roof

The trading of air pollutant emissions from power plants reduces the total amount of emissions entering the environment through emission caps and creates demand for pollution abatement technologies. Although trade programs credit pollution abatement, the focus is placed on reduction of emissions at the source (see Figure 2.2). This ignores the roles of pollutant sinks and their potential regional impact by reducing air pollution through increased green space as afforded by vegetated roofs. This section summarizes the history, configuration, and design issues of vegetated roofs commonly known as green roofs.

2.3.1. History

Roofs provide a waterproof and thermal barrier between humans and the natural environment surrounding their built environment. Because of its functional purpose, it may seem counterintuitive to place plants on top of a roof. However, vegetation on roofs has provided aesthetics (the hanging gardens of Babylon) and function (the sod roofs of Scandinavia) for thousands of years (Dunnett and Kingsbury, 2004). Figure 2.3 depicts a traditional green roof in Sweden. Vegetated roofs were originally used as thermal insulation. In Scandinavia, insulation aided in retaining heat while in hotter climates such as Tanzania and Kurdistan, vegetated roofs assisted in keeping interiors cool (Dunnett and Kingsbury, 2004).

Figure 2.3 Traditional Scandinavian green roof in Skansen, Stockholm, Sweden (photograph by author).

The modern green roof appeared in the middle of the nineteenth century with a planted concrete “nature roof” at the 1868 World Exhibition in Paris (Dunnett and Kingsbury, 2004). At the beginning of the twentieth century, green roofs were utilized as roof gardens in building projects by architects Frank Lloyd Wright and Le Corbusier (Dunnett and Kingsbury, 2004; Peck and Kuhn, 1999). While several projects in the 1960s and 1970s integrated plants and buildings in Germany and Switzerland, the occurrence of leaks and problems with root penetration remained technical challenges until the 1980s. While green roof research began in Germany in the 1950s as part of ecological and environmental research in urban habitats, research began in earnest in 1977 through the formation of a green roof study group within the FLL (Forschungsgesellschaft Landschaftesentwicklung Landschaftsbau: Research Association of Landscape Development and Landscape Gardening). Hans-Joachim Liesecke and Walter Kolb were among the first who established that roof greening has benefits for energy conservation and minimizing water runoff (Dunnett and Kingsbury, 2004).

2.3.2. Design and Function

While the functions of modern green roofs remain the same as traditional vegetated roofs (i.e. protection from water and thermal insulation), the components have evolved over the years. Structurally, green roofs are now similar to modern asphalt roofs. Figure 2.4 shows a typical structure of a contemporary green roof.

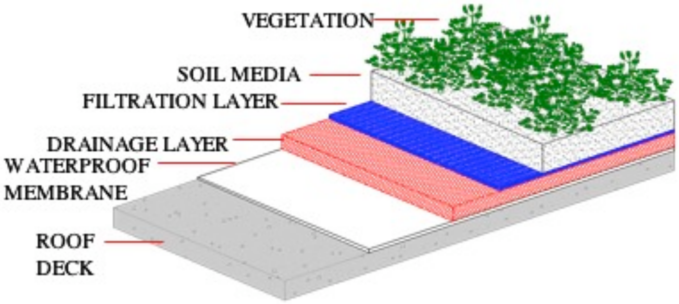


Figure 2.4 Components of a green roof (adapted from Barbour et al., 2005).

From the figure, one can see that in addition to a waterproofing layer that is found on conventional roofs, green roofs have a drainage layer, a solid matrix “soil” layer, and vegetation. Rainwater that is not evapotranspired through the aid of vegetation percolates through the soil media to the drainage area where it flows off the roof through a conventional drainage system. The additional layers of a green roof protect the roofing membrane that is normally exposed to weathering and ultraviolet light degradation on a conventional roof. As a result, while asphalt roofs typically last twelve to fifteen years (Patterson and Mehta, 2001), green roofs can last twice or thrice as long as standard roofs upwards of forty years (Köhler, 2006). The following is a description of the different components of the green roof:

i. Vegetation: Plants provide aesthetic value while contributing to the reduction and delay in stormwater runoff by storing water in their leaves, roots, and bulbs. Sedums and other succulents are the most commonly used vegetation due to their ability to survive in severe weather with little soil. Soil Media**:** This layer forms the growing medium for the plants and absorbs and retains water in a controlled manner. The substrate usually consists of 10-15% organic material to provide nutrition for plant growth under the assumption that a healthy green roof should supply its own organic material though decomposition of plant material. Filtration

Layer: The layer separates the soil media from the drainage layer preventing clogging by trapping small substrate particles. Roots can penetrate this layer to reach water stored in the drainage layer.

iv. Drainage Layer: The drainage layer draws and drains excess water away from the roofing membrane. There are two general types of drainage layers, granular and plastic boards.

v. Root Barrier: This barrier protects the waterproofing membrane from plant root penetration. If the waterproofing membrane is root resistant, this barrier is not necessary.

vi. Waterproofing Membrane and Structure: This layer is found in all conventional roofs as it protects the roof deck and building from weathering. This is often of bitumen or plastic (PVC) construction.

Extensive roofs have substrate depth ranges from 2.5 cm to 15 cm with an average saturated weight between 48.8 kg/m^2 to 170.9 kg/m^2 (GRHC, 2006). Extensive green roofs are not designed for frequent access, but they do have access for routine maintenance. In addition to being lightweight, extensive green roofs require low capital cost and require minimal maintenance (Peck and Kuhn, 1999). Due to the limited substrate layer of extensive roofs and the weather extremes on roof surfaces, sedums are a popular choice of vegetation on extensive systems. Sedum have leaf surfaces that aid in water retention and evapotranspiration, and their short, horizontally directed, non-penetrating roots make them excellent choices for green roofs. Resilience studies of sedum have shown that although the volumetric moisture content of a green roof can be reduced to 0 m^3_{water}/m^3_{bulk} within one day depending on substrate depth, sedum can remain viable after 88 days of drought (VanWoert et al., 2005a). Recommendations from this study suggest that water should be applied at least every 28 days for typical extensive roof substrate depths and every 14 days for those with shallow (2-cm) depths. Figure 2.5 shows a picture of a typical extensive green roof in Southfield, Michigan

Figure 2.5 Extensive green roof at Lawrence Technological University in Southfield, Michigan (photograph by author).

Intensive roof systems are primarily installed for aesthetic value and are often designed to be regularly accessible as roof gardens. These systems are heavier, more expensive, and require higher maintenance than extensive green roofs. The growing medium is deeper than extensive roofs and usually ranges between 20 cm to 60 cm (Peck et al., 1999). Due to the deeper soil layer, intensive roofs typically range between 244.1 kg/m^2 and 1464.7 kg/m^2 (GRHC, 2006). The depth of the growing medium permits the addition of many more plants, which may increase maintenance costs. An intensive green roof is shown in Figure 2.6 at the Solaire Building in New York City.

Figure 2.6 An intensive green roof on the Solaire Building, New York, New York (photograph by author)

A *semi-intensive roof* is an intermediate between an extensive roof and an intensive roof. The media depth is typically between 12 cm and 20 cm with the fully saturated weight between 170.9 kg/m^2 and 244.1 kg/m^2 (GRHC, 2006). The semi-intensive roof can provide greater plant diversity than the extensive roof by utilizing parts of the roof with greater load capacity. An example of a semi-intensive roof system is shown in Figure 2.7.

Figure 2.7 An example of a semi-intensive green roof in Augustenborg, Sweden (photograph by Andrew Turner).

2.3.3. Building Considerations and Code Issues

As green roofs become more established within the US building community, the need for standardization of good building practices increases. ASTM International has published four *Green Roof Performance Standards* and one standard guide.

- ASTM E2396-05 Saturated Water Permeability of Granular Drainage Media;
- ASTM E2397-05 Determination of Dead Loads and Live Loads Associated with Green Roof Systems;
- ASTM E2398-05 Water Capture and Media Retention Standards of Geocomposite Drain Layers for Green Roof Systems;
- ASTM E2399-05 Maximum Media Density for Dead Load Analysis of Green Roof Systems; and

- ASTM E2400-06 Standard Guide for Selection, Installation, and Maintenance of Plants for Green Roofs.

The method for determining water permeability of coarse granular materials used in the drainage layers of green roof systems (E2396-05) also assists in determination of the dead load. The dead load and live load determination standard (E2397-05) provides a procedure for predicting the system weight of a green roof system. The weight assessment accounts for components that are typically encountered in green roof systems. The weight is determined under two conditions. Dead load is the weight of the system under drained conditions and the weight of retained water or other precipitation. The second scenario assesses the weight when precipitation is actively occurring and the drainage layer is saturated. The difference in weight between the first (dead load) and second conditions is considered a live load. To determine the saturated weight, (E2398-05) the standard method for water capture and media retention of the drainage layer would be used. This standard is applicable to geocomposite drains layers that retain water and media in cup-like receptacles on their upper surface (e.g. shaped plastic membranes). The standard method for maximum media density (E2399-05) assists in determining the dead load by providing a measure of the moisture content and the water permeability measured at the maximum media density. The plant selection, installation, and maintenance guideline (E2400-06) is applicable to both extensive and intensive green roof systems.

Two additional standards are currently under development. ASTM WK575 Practice for Assessment of Green Roofs will include technical requirements and sustainable development considerations (ASTM, 2003). Assessment of some technical requirements may refer to existing green roof standards. Fire safety will likely need additional standards developed for proper assessment. Assessment for sustainability considerations may include energy efficiency, water management, and biodiversity. The other standard under development is the ASTM WK7319 Standard Guide for Use of Expanded Shale, Clay, or Slate (ESCS) as a Mineral Component in Growing Media for Green Roof. This standard describes the characteristics of the material to be a mineral amendment and covers the sampling appropriate for the procedure (ASTM, 2007).

2.4. Benefits of Green Roofs

There are many benefits to green roofs. The two most investigated benefits are related to energy consumption (heating/cooling) and the reduction and delay of stormwater runoff. What follows is a summary of the literature in both of these areas and initial studies into air pollution mitigation benefits of green roofs.

2.4.1. Energy Benefits

Although modern vegetated roofs have been in existence in Germany for at least thirty years, the literature on the energy benefits of green roofs developed in the late 1990s. The majority of research has focused on quantifying the insulative abilities of green roofs in summer. In summer months, green roofs behave as a high quality insulator reducing the flux of solar radiation in a building (Del Barrio, 1998; Niachou et al., 2001). Using a conductance of 0.42 W/m^2/K for a green roof, Saiz et al (2006), reported summer cooling load reductions of 6% for an eight-storey building with peak hour cooling load reductions in the upper floors reaching 25%. Insulation layers may retard heat flux in situations that are undesirable. While insulation reduces cooling load for hours when outside temperature is higher than inside temperature, the insulation retards heat loss for those hours the internal temperature exceeds external temperatures (Akbari, 2003). For a dark roof, the negative impact on air conditioning (AC) usage during hours where external temperatures were below internal temperatures was greater than for a white roof, suggesting that both roof insulation and roof reflectivity should be assessed to minimize energy use in buildings.

A recent study on the surface heat budget on a green roof and high reflectivity roofs revealed that the sensible heat flux is small compared to concrete roof surface on both a highly reflective white paint surface and a green roof (Takebayashi and Moriyama, 2007). It is understood that the heat flux is small on the white roof due to the low net radiation. In contrast, the green roof had a large net radiation. The small sensible heat flux for the green roof was due to the large latent heat flux by evaporation (Takebayashi and Moriyama, 2007).

The two main parameters that influence the solar radiation that reaches the roof deck are the following:

- Leaf foliage, and
- Soil thickness.

Aspects of the leaf foliage that influence solar radiation include the leaf area index (LAI) and leaf angle distributions, which both affect the shadowing ability of plants (Del Barrio, 1998). Additionally, the larger the foliage development of a particular plant, the more the heat flux through the roof decreases (Del Barrio, 1998; Niachou et al., 2001; Theodosiou, 2003). Surface temperatures have been observed to vary according to the LAI (Wong et al., 2003).

Soil thickness also plays an important role in heat transfer. It was observed that thick soil layers resulted in cooling ability during summer months while thin substrate layers resulted in little to no cooling benefit (Theodosiou, 2003). Roofs with substrates between 7.5 cm and 10 cm reduced the average daily heat flow throughout the year (Liu and Minor, 2005). The observed reduction in heat flow were greater in the summer months (70-90%) than in the winter (10-30%) (Liu and Minor, 2005). Heat transfer is greater on those roof surfaces not covered with a green roof (Niachou et al., 2001; Wong et al., 2003) although the vegetated roof should not serve as a replacement for insulation (Eumorfopoulou and Aravantinos, 1998).

Secondary parameters that influence heat transfer and roof surface temperatures include relative humidity and wind speed. Varying these parameters has less of an effect on heat flux than LAI or soil media thickness. A dry environment increases the rate of evapotranspiration aiding the absorbance of solar radiation by plants (Theodosiou, 2003; Niachou et al., 2001). Wind speed contributes to a smaller increase in evapotranspiration rate.

Several modeling studies have attempted to connect the heat and mass transfer that occurs within a green roof system to the energy savings that may be observed in a building. Recently, Alexandri and Jones (2007) found that a 1-dimensional heat and mass transfer algorithm improved on the predictive capabilities of energy consumption than a heat transfer only system, suggesting that the connection between thermal diffusion and moisture transfer should not be ignored. A humid porous media model simulated the cooling effect of water evaporation on a roof with porous media under various weather conditions (Meng and Hu, 2003). It was found that the outer surface temperature of the media was lowered by 25 °C and the inner roof surface was lowered by 5 °C (Meng and Hu, 2003). Variations according to depth and climate conditions were not investigated.

Several studies have incorporated landscaping into DOE-2, which has been adopted as the freeware, standard building energy use model. Akbari et al. (1997; 2001) modeled the effects of trees on buildings in DOE-2 model, and compared the effects of light and dark roofs with and without trees. Air conditioning energy savings of 20% were realized for modeled buildings utilizing cool roofs and trees in Los Angeles, California (2001). Recently, DOE-2.2 version 44e4 (February 2007) was released with an ecoroof component that has the capability to simulate the heat transfer on a vegetated roof.

2.4.2. Stormwater Quantity and Quality Benefits

When rain falls on forested and open undisturbed land, thirty percent of the water reaches shallow aquifers that feed plants, another thirty percent percolates and nourishes deeper aquifers, and approximately forty percent returns to the atmosphere through evaporation and plant transpiration (Scholz-Barth, 2001). Figure 2.8 depicts the changes in rainwater distribution according to the degree of impervious surface.

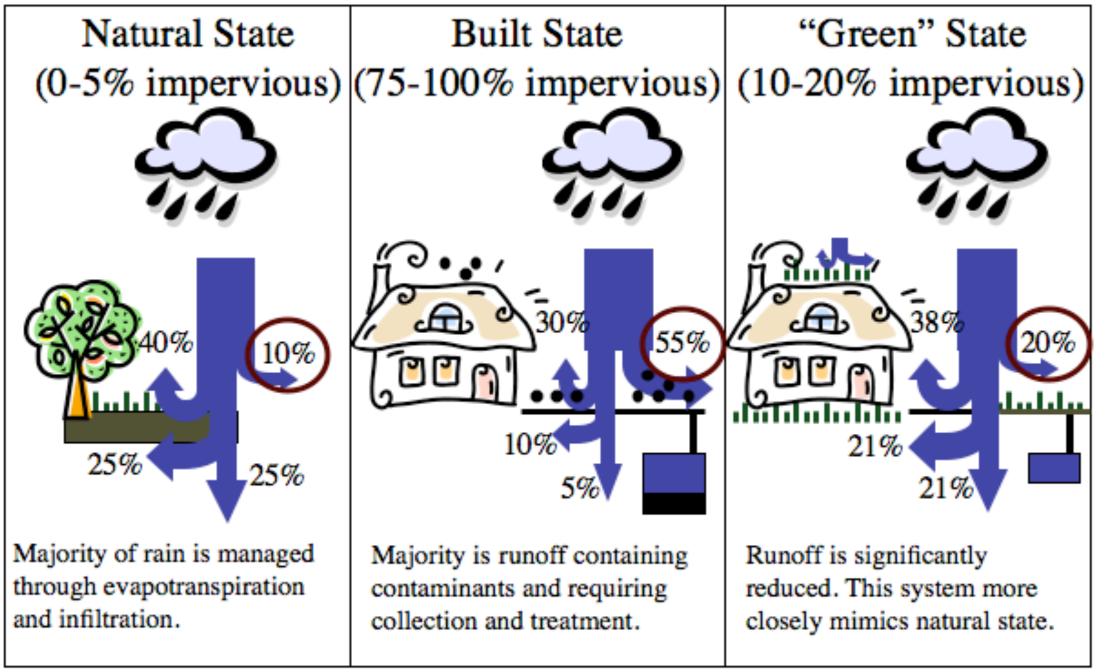


Figure 2.8 Distribution of rainwater in natural and built environments (adopted from Scholz-Barth, 2001).

In metropolitan areas, seventy-five percent or more rainwater become stormwater runoff. Green roofs and other porous surfaces can correct the rainwater distribution reducing the demand on sewer systems.

Depending on the climate of a region, green roofs can retain as much as fifty to seventy percent of water that falls onto a roof. Hutchinson et al (2003) report that during a 15-month monitoring period beginning in 2002, a 10 to 12 cm vegetated roof in Portland, Oregon retained 69% of the total rainfall with peak flow reductions of 80%. Moran et al (2005) evaluated retention and peak flow reduction for a roof in Goldsboro, North Carolina. Total rainfall retention was 55% (10 cm roof with 7% slope) and 63% (7.5 cm flat roof) for both green roofs (Moran et al., 2005). Peak flow reduction was 57%

for the sloped roof and 87% for the flat roof. Higher volume rain events resulted in smaller peak flow reductions.

VanWoert et al (2005b) also evaluated the effect of roof type, slope, and substrate depth on stormwater retention. Initial investigations compared a gravel roof and a vegetated roof, the mean percent rainfall retention ranged from 48.7% for a gravel roof to 82.8% for a vegetated roof in East Lansing, Michigan (VanWoert et al., 2005b). Two slopes were tested, 2 percent and 6.5 percent, and 3 green roof substrate depths were evaluated at 2.5, 4.0, and 6.0 cm. The greatest retention for all rain events at 87% occurred on a 2% slope roof with a media depth of 4 cm. The retention for a 2 percent slope was confirmed by Getter et al. (2007) in a study considering four roof slopes (2, 7, 15, and 25 percent) where the 2 percent slope had a mean retention of 85.6% and the 25 percent slope retained the least (76.4%).

Further studies on the effect of slope were conducted for the 4 cm roof by Villarreal and Bengtsson (2005). The slopes evaluated ranged from 2-14 degrees under dry conditions and wet conditions (field capacity) located in Lund, Sweden. Results from this study showed no effect on the direct runoff hydrograph from slope variation. The difference in peak flows and total stormwater volume retention was affected by the moisture content of the roof. Dry conditions required 6 to 12mm of rain prior to runoff initiation while wet conditions resulted in nearly immediate runoff (Villarreal and Bengtsson, 2005).

Water quality from roof runoff has been investigated as well. Zobrist et al (2000) evaluated roof runoff for two conventional roofs common to Switzerland (tile and polyester) and a gravel roof. The concentration of heavy metals on the conventional roofs was of the same magnitude as the depositional load. The gravel roof retained most heavy metals and phosphorus while producing calcium and alkalinity, which were beneficial changes (Zobrist et al., 2000). However, the gravel roof supported nitrification and contributed significant levels of copper from the drainage system. Mason et al (1999) reported that roof material were significant sources of calcium, magnesium, sodium, potassium, and chlorine as observed values in runoff exceeded depositional loads. Bucheli et al. (1998) evaluated runoff from a grass roof and determined that excess levels of an herbicide (R, S) mecoprop were due to placement of the chemical on the roof membrane to retard root growth. While green roofs have the potential to retain materials from atmospheric deposition, material choices affect stormwater runoff quality.

The Toronto and Region Conservation office evaluated a green roof in Toronto, Canada for water quality, as part of the Sustainable Technologies Evaluation Program. Total suspended solids, kjeldahl nitrogen, *Escherichia coli*, aluminum, copper, zinc, phenanthrene, and fluoranthene were all observed at lower concentrations in the green roof runoff that the conventional roof. For this roof, however, there were excessive levels of phosphorus in the green roof runoff (TRC, 2006).

Stormwater modeling has shown the potential benefits for large-scale roof-greening projects. For Washington, DC, greening 2 million square meters of rooftops would store over 1.6 million cubic meters annually (Deutsch et al, 2005). While the roofs would only reduce citywide runoff by 1.7 percent, the volume captured would reduce the total number of combined sewer overflows (CSOs) that discharge untreated sewage into waterways by fifteen percent (Deutsch et al., 2005). The ability of green roofs to reduce and delay stormwater is one benefit that has received the attention of policymakers.

A more detailed study evaluated two planning scenarios with green roofs as one management tool. Scenarios were evaluated with a continuous simulation hydrologic and hydraulic model under average annual rainfall conditions for Washington, DC. Reductions in volumes, and discharge frequency were based at the sewershed scale. The intensive greening scenario, adding trees and green roofs wherever it was physically possible, was estimated to retain over 1.2 billion gallons (4.5 million cubic meters) of stormwater (a 10% reduction), while accomplishing a 6.7% reduction in CSO frequencies. A moderate greening scenario emphasizing practicality of green roof implementation retained over 311 million gallons (1.2 million cubic meters) of stormwater (a reduction of 3%), and a 1.5% reduction in cumulative CSO frequencies. These reductions could result in savings between $1.4 and $5.1 million per year in annual operational savings for the Washington Area Sewer Authority in the CSS area due to reduced pumping and treatment costs (Deutsch et al., 2007).

2.4.3. Air Quality Improvement by Vegetated Roofs

To incorporate green roofs into an emissions trade program, the uptake capacity of a roof must be quantified.

Indirect Pollution Reduction

As elevated temperatures accelerate the production of ground level ozone and smog, reducing the heat island effect through greening roofs indirectly reduces ozone and smog generation. Greening fifty percent of New York City is estimated to reduce the average surface temperature by 0.1 to 0.8 degrees Celsius (Rosenzweig et al., 2006). Cooling urban areas also reduces vertical thermal air movements reducing the stirring of particulate matter in the air (Peck et al., 1999). As green roofs assist in lowering the cooling demand in buildings, the subsequent reduction in electrical demand can lead to power plants burning less coal. Less coal burned would result in fewer NO_X, SO_2, CO_2, and mercury emissions. Greening 6 percent of Toronto has the capability of reducing the urban heat island effect by 1 to 2 ºC, which would reduce greenhouse gases by 0.62 MT (Mega tons) indirectly from urban heat island reduction (Peck et al., 1999).

Direct Pollution Reduction

Few studies exist that have measured direct removal rates of air pollutants by green roofs. Single roofs are not assumed to contribute significantly to improvement in urban air quality (Sutic, 2002). Nevertheless, 2000 m^2 of un-mowed grass on a roof is estimated to remove as much as 4 Mg of particulates from the surrounding air (Johnston and Newton, 2004). A pilot green roof study in Singapore had mixed results on air quality changes; Yok and Sia (2005) noted reductions of SO_2 by 37% and nitrous acid (HONO) by 21%. They also showed increased nitric acid (HNO_3) by 48% and particulate material (both PM 2.5 and 10) presumably from resuspension related to gravel ballast and bare areas on the green roof (Yok and Sia, 2005).

Improvements are more likely to occur from large-scale greening efforts. Research conducted by Environment Canada determined that current roof greening covers 6% of the roof area in Toronto (over 6.5 million square meters) and has resulted in a 5-10% reduction in NO_X and SO_2 concentrations in the air, and uptake of 30 tons of particulate matter (Peck, 2003). The pollutant uptake estimates are based upon the Urban Forest Effects (UFORE) model.

The United States Department of Agriculture (USDA) Forest Service's UFORE computer model helps quantify urban forest structure and functions. It was developed in late 1990s at the USDA Forest Service, Northeastern Research Station in Syracuse, NY. The model quantifies a number of parameters from local measurements including the urban forest structure (e.g. species composition, tree density and health), hourly volatile organic compound (VOCs) emissions by the forest, hourly pollution removal by the forest and percent improvement in air quality, total carbon stored and sequestered annually, and effects of trees on energy consumption and subsequent CO_2 emissions by buildings (Nowak et al., 2005). The model is dependent upon plant species but does not include data for sedum, the traditional type of plant for green roofs. Assuming a 50:50 mix of grasses and evergreen shrubs, two studies have evaluated the potential benefit of green roofs using this model (Bass et al., 2004; Deutsch et al., 2005).

The study by Bass et al. (2004), evaluated pollution removal rates for six scenarios of city greening (e.g. trees, shrubs, green roofs) for midtown Toronto. One scenario evaluated potential annual uptake of NO_2, $S0_2$, CO, PM10, and ozone by green roofs and the subsequent economic value of pollutant removal. Table 1 shows the results from potential greening of 20 percent of midtown rooftops. The economic value of health benefits for pollution uptake were estimated to be 43,100 $US per year. The study conducted by Casey Trees Endowment Fund and Limno-Tech evaluated the potential air pollution removal by greening rooftops in Washington, DC. Results from greening approximately 2 million square meters of rooftops are shown in Table 2.2. Economic data was not supplied for these results, but the pollution reductions were determined to be comparable to 25 percent of the 105,900 street trees currently in Washington, DC (Deutsch et al, 2005).

Table 2.2 Estimated benefits of roof greening projects in Toronto and Washington, DC using the Urban Forest Effects Model (Bass et al., 2004; Deutsch et al, 2005).

Pollutant	**Toronto Annual Removal (Mg)**	**Washington, DC Annual Removal (Mg)**
	109.386 ha of green roof	185.806 ha of green roof
CO	0.35	0.77
NO2	1.6	2.17
O3	3.14	6
SO2	0.61	2.21
PM10	2.17	5.66

There are several limitations with this model: (i) it does not include pollutant uptake data by sedum, and (ii) it does not predict effects on water quality. Currently, the model is not available to the public. All data must be submitted to the researchers for analysis.

2.5. Nitrogen Oxides and the Environment

To model the interactions of nitrogen oxide emissions with the vegetation and soil compartments, the complex nitrogen oxide chemistry within the environmental compartments must be understood. A basic description of nitrogen oxide cycling will be described with the bulk of the section devoted to understanding of the complex chemistry within urban, polluted areas in the presence of anthropogenic emissions.

2.5.1. Tropospheric Nitrogen Oxide Chemistry

Both short-stack and tall-stack anthropogenic nitrogen oxide emissions enter into the troposphere. With vehicular emissions as another significant source of nitrogen oxides, much of the reactive chemistry focuses on nitrogen oxides in urban areas. The nitrogen may be present in the fuel or a result of thermal decomposition of air inside the combustion chamber. At high temperatures, NO is produced via the following reaction sequence:

$$O_2 + \text{heat} \Leftrightarrow O + O \qquad \text{(R 2.1)}$$

$$O + N_2 \Leftrightarrow NO + N \qquad \text{(R 2.2)}$$

$$N + O_2 \Leftrightarrow NO + O \qquad \text{(R 2.3)}$$

NO and nitrogen dioxide (NO_2) rapidly cycle in the atmosphere, and as a result, both NO and NO_2 are considered primary pollutants.

Cycle 1

$$HO_2 + NO \Rightarrow OH + NO_2 \qquad \text{(R 2.4)}$$

$$NO_2 + h\upsilon + O_2 \Rightarrow NO + O_3 \qquad \text{(R 2.5)}$$

Cycle 2

$$NO + O_3 \Rightarrow NO_2 + O_2 \qquad \text{(R 2.6)}$$

$$NO_2 + h\upsilon + O_2 \Rightarrow NO + O_3 \qquad \text{(R 2.5)}$$

These primary pollutants form ozone via photochemical reactions with hydroxyl radicals and volatile organic compounds (VOCs) (Sillman, 2003). See Sillman's chapter on tropospheric ozone in *Treatise on Geochemistry: Volume 9, Environmental Geochemistry* for further information on the production of ozone (Sillman, 2004). Subsequent reaction sequences lead to the production of nitric acid (HNO_3), the principal sink of NO_X (Sillman, 2003; Jacob, 1999):

Daytime

$$NO_2 + OH + M \Rightarrow HNO_3 + M \qquad \text{(R 2.7)}$$

Nighttime

$NO_2 + O_3 \Rightarrow NO_3 + O_2$ (R 2.8)

$NO_3 + NO_2 + M \Rightarrow N_2O_5 + M$ (R 2.9)

$N_2O_5 + H_2O + \text{aerosol} \Rightarrow 2HNO_3$ (R 2.10)

For this reason, the lifetime of NO_X is on the order of one day. Nitric acid in the troposphere is primarily removed by deposition within a few days in the lower troposphere and a few weeks in the upper troposphere (Jacob, 1999).

2.5.2. Nitrogen Oxides and Vegetation

Nitrogen oxides alone, or in combination with other air pollutants such as ozone, sulfur oxides, and particulate materials (PM), can cause respiratory diseases and increase the risk of heart attacks (Brunekreef and Holgate, 2002) (Bell et al., 2004). Damage from NOx extends to plants as well, resulting in reduced growth, respiration, photosynthesis, stomatal conductance, and enzyme activities(Wellburn, 1990; Rantanen et al., 1994).

Nevertheless, there is increasing evidence that plants take up NO_2 from the atmosphere. Hill (1971) proposed that vegetation may serve as a sink for atmospheric contaminants, and Rogers et al. (1979) observed assimilation of NO_2 by *Phaseolus vulgaris*. It has been assumed that primary nitrogen assimilation pathways convert NO_2 into organic nitrogenous compounds (Rogers et al., 1979; Yoneyama and Sasakawa, 1979; Kaji et al., 1980; Wellburn, 1990). Morikawa et al. (Morikawa et al., 2004) indicated that NO_2 can also be converted to alternative nitrogen compounds allowing NO_2 to serve in a limited capacity as a nitrogen fertilizer. The extent of NO_2 uptake depends upon the atmospheric concentration (Rogers et al., 1979; Takahashi et al., 2005) and the plant species (Durmishidze and Nutsubidze, 1976; Morikawa et al., 1998; Takahashi et al., 2005).

When considering the uptake and incorporation of reactive nitrogen compounds in vegetation, there are generally two methods of transport into the plant; these are depicted in Figure 2.9. Compounds may be taken up by vegetation through partitioning from soil to the plant roots and then transported via the xylem (Morikawa and Erkin, 2003). Reactive nitrogen compounds can also deposit directly from the air via gas-phase and particle-phase dry and wet deposition (Hanson and Lindberg, 1991; Simonich and Hites, 1995; Sickles and Shadwick, 2007).

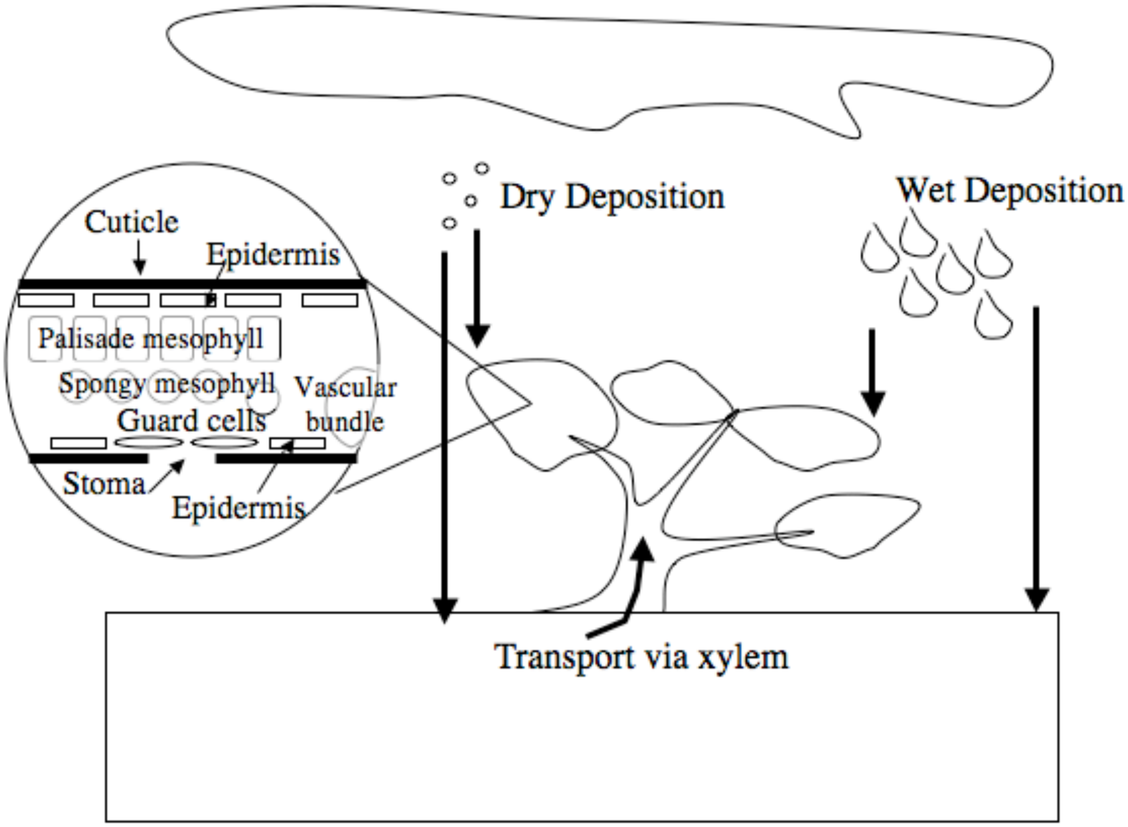


Figure 2.9 Transport mechanisms between the air-soil-vegetation system.

For these compounds, exchange occurs on the cuticle of the leaf or via the stomata (Nobel, 2005). The cuticle is a waterproof layer comprised of cutin on the epidermal cells of the leaf. Cutin is a relatively inert compound that protects the leaf from degradation and water loss (Nobel, 2005). The stomata are pore spaces between two guard cells of the epidermis that allow CO_2 and other trace gases into the leaf for photosynthesis. O_2 and water vapor are emitted through these pore spaces as well, and the spaces are adjustable to balance the influx of CO_2 required for photosynthesis with the inevitable water loss that occurs when the stomata are open (Nobel, 2005).

Uptake of Nitrogen Dioxide (NO_2)

Leaf-level measurements are available for nitrogen dioxide (NO_2) from a variety of plant species. According to Hanson and Lindberg (1991), broadleaf and crop plants tend to have higher conductance (mean conductance between 1.2 and 1.3 mm s^{-1}) than conifer trees (mean conductance between 0.3 and 0.8 mm s^{-1}). Generally, the uptake rate increases proportionally to the atmospheric concentration of NO_2. There is evidence of a 'compensation point' where below concentrations of 3nl l^{-1}, NO_2 would not deposit (Johansson, 1987). This compensation point may apply to rural areas but is below ambient concentrations in urban areas.

Several studies have shown that stomatal aperture controls NO_2 deposition (Saxe, 1986; Hanson et al., 1989; Okano et al., 1989). Hanson and Lindberg (1991) state that while cuticular deposition rates have been reported at 1-2 orders of magnitude less than stomata deposition, it should be included in calculations of NO_2 deposition.

Uptake of Nitric Oxide (NO)

The observed conductance of nitric oxide from trees and crops is less than reported values for NO_2. Stomatal conductance controls NO uptake although there is a cuticular pathway as well (Hill, 1971; Galbally, 1989). Additionally, there is a compensation point for nitric oxide. Under denitrifying conditions, there is a potential for NO to volatilize from soil although the secondary denitrifying emission tends to be nitrous oxide (N_2O). NO is emitted in much smaller amounts (Galbally, 1989). When soil moisture content is at saturation, very little NO is emitted. The greatest potential for NO emission from soils occurs on soils where the biomass has burned (Galbally et al., 1987; Johansson and Granat, 1984). Under vegetated conditions, the flux of nitric oxide to the atmosphere is significantly reduced (Galbally, 1989).

Uptake of Nitric Acid

Nitric acid (HNO_3) has been reported to have higher rates of deposition than other oxides of nitrogen. Vapor deposition varies from less than 5 to 27 nmol/m^2/s (Hanson and Garten, 1992). Deposition is dependent upon the plant type. While whole leaf conductance for hardwoods was lower (0.9- 3.4 mm/s) than for a loblolly pine (6-34 mm/s), 39-48 percent of the deposited nitric acid remains bound in the hardwoods and only 3 percent of the nitric acid remains bound to loblolly pine needles (Hanson and Garten, 1992). This suggests that elevated concentrations of nitrate are more likely to occur in throughfall from conifers than hardwoods during rain events (Hanson and Garten, 1992). According to Marshall and Cadle (1989) and Cadle et al. (1991), nitric acid deposition may occur along sorption sites on the leaf surface (cuticle) as well as the metabolically active leaf interior (via stomata). Deposition of HNO_3 is highly sensitive to leaf boundary layer resistance and may predominate via deposition to the cuticle (Hanson and Garten, 1992).

When considering nitric acid deposition, one may be interested in assessing nitrate as well. However, Meyers et al. (1991) found that nearly all deposited nitrogen

(HNO_3+NO_3^-) was in the form of HNO_3. Dry deposition was estimated to provide between 30-50% of total input from atmosphere for observed sites in the eastern US (Meyers et al, 1991). Both dry and wet deposition play a role in the reactive nitrogen species exchange between air-plant-soil surfaces.

Factors Affecting Uptake by Vegetation

Several factors affect uptake of reactive nitrogen species by vegetation, and are directly related to their water solubility, vapor pressure, and octanol-water partitioning coefficient. Environmental conditions such as temperature, pH, organic matter content, and soil moisture content also have an effect. Plant-specific characteristics including the type of root system and enzymes secreted to the rhizosphere affect uptake as well (Susarla et al., 2002). Lipophilic compounds (those with K_{OW} greater than 10^4) partition to the epidermis of the root or to the soil particles and tend to not be drawn into the inner root xylem of the plant (Simonich and Hites, 1995). As a result, those compounds are often not translocated into the plant and not significantly metabolized (Simonich and Hites, 1995; Trapp et al., 1990). Hydrophilic compounds are taken up from the soil through the root system for compounds with high water solubilities, low Henry's constants, and low K_{OW} values (Simonich and Hites, 1995; Morikawa and Erkin, 2003). These compounds can be taken up by the plant and metabolized (Simonich and Hites, 1995).

2.6. Modeling of Fate and Transport in Environmental Systems

In devising methods to minimize the adverse effects of electric utility emissions and other chemical emissions to the environment, it is necessary to understand the environmental behavior of the contaminant within and between air, soils, water, and biota. While the partitioning of a substance in the environment can be expressed as the chemical potential of a substance in each phase, the simpler concept of fugacity was introduced in 1901 (reviewed by Mackay, 2001). The use and acceptance of fugacity in environmental partitioning and chemical equilibrium calculations developed in the last twenty-five years.

This section explains *fugacity* and the development of multi-compartment modeling using a fugacity approach and includes a discussion on the integration of the vegetation compartment in multi-compartment modeling.

2.6.1. Definition of Fugacity

Fugacity is the tendency for a chemical substance to “escape” from one phase to another phase and has units of pressure (Mackay, 1979; 2001). When the “escaping” tendencies or fugacities of two phases are equal, they are said to be in equilibrium. For most low concentrations of chemical substances of environmental interest, a substance’s fugacity in a phase is linearly proportional to concentration (e.g. ten molecules of a substance exert ten times the fugacity of one molecule of a substance). One can relate fugacity to temperature. Mass diffuses from high to low fugacity. It is important to note that the direction of diffusion is not always obvious from the concentration of a substance in a phase, but it is obvious when in units of pressure (fugacity) (Mackay, 1979).

The simplest case for determining fugacity is a solution in the gas phase (air). Assuming no reaction, the basic fugacity equation is the following:

$$f = y\phi P_T \tag{2.1}$$

where y is mole fraction, ϕ is a fugacity coefficient, and P_T is atmospheric pressure. Assuming that the ideal gas law applies to diffuse concentrations of environmental significance, let P be the partial pressure, yP_T. The concentration (mol/m^3) of the solute in the gas phase is the following:

$$C_A = \frac{yP_T}{RT} = \left(\frac{1}{\phi RT}\right)f = Z_A f \tag{2.2}$$

where R is the gas constant, T is absolute temperature in Kelvin, Z is the proportionality constant or *fugacity capacity* (mol/m^{3}Pa). Assuming that the fugacity coefficient, ϕ, is unity under environmental conditions, the fugacity capacity is constant and *fugacity* is numerically equal to partial pressure for the gas phase (Mackay, 2001). The fugacity of a contaminant can be determined from the fugacity capacity and the concentration of the component for each compartment. The computer models from the CEMC are based upon this idea.

2.6.2. Fugacity Approach to Multi-Compartment Modeling

Fugacity can be a useful tool in identifying the static or dynamic behavior of substances in environmental systems. The approach is also valuable in determining the dominant processes for substance degradation or removal within environmental systems (see Figure 2.10).

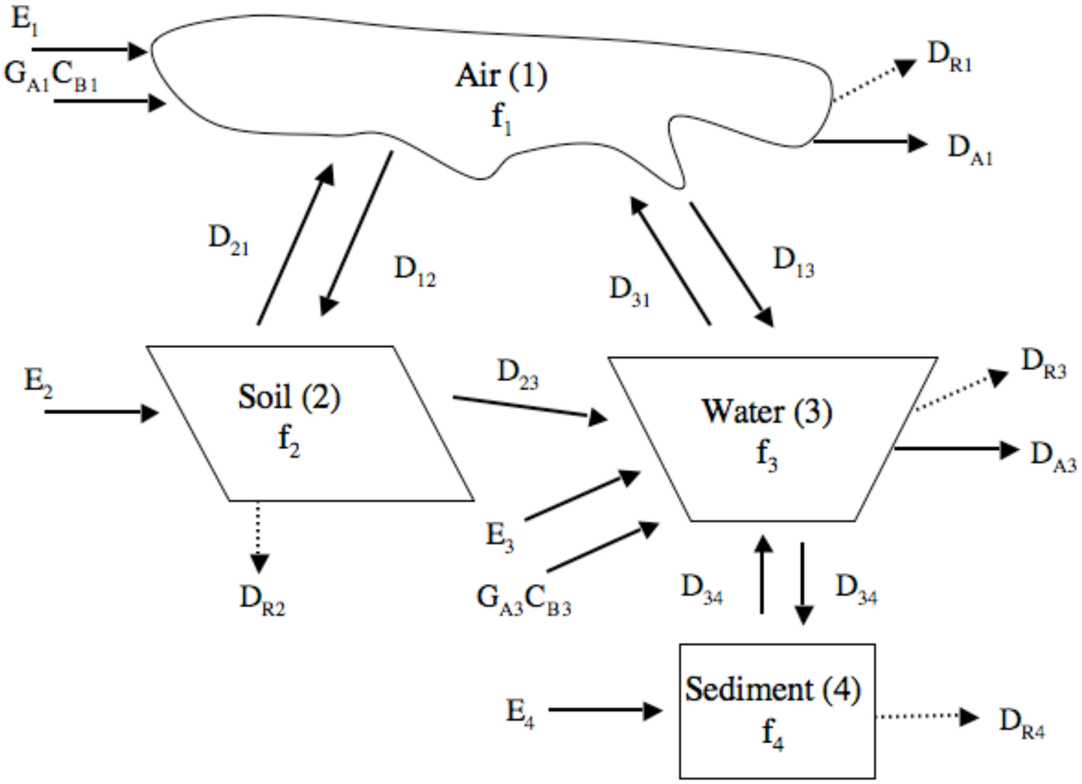


Figure 2.10 General schematic of a fugacity model (modified from Mackay, 2001).

Level 1 Model Framework

Simple analysis provides information on the equilibrium distribution of a fixed amount of a chemical substance without transformation. This analysis ignores inputs, outputs, and transformations of a chemical and assumes that intercompartment transfer is fast. The Level 1 analysis describes the ultimate distribution of a persistent substance in the environment in terms of relative concentrations and relative masses (Mackay, 1979). Level 1 analysis cannot be used to predict concentrations of a chemical substance.

Level 2 Model Framework

The Level 2 analysis assumes that all environmental compartments are in equilibrium as in Level 1 analysis. Additionally, Level 2 assumes a steady-state input of the solute and incorporates transformations by photolysis, hydrolysis, oxidation, biodegradation, and advection of solute of the system (Mackay, 1979).

Level 3 Model Framework

Level 3 calculations build upon Level 1 and Level 2 analyses. A Level 3 analysis assumes steady-state input, transformation, and intercompartment transfers (Mackay, 1979). Additionally, the contaminant entering the system can be introduced into one or more of the compartments. This level does not assume equilibrium and the transfer rate between compartments is driven by the fugacity difference (Mackay, 1979).

Level 4 Model Framework

Level 4 calculations assume neither steady-state nor equilibrium. The input rates, concentration, and fugacity may vary with time. The unsteady-state distribution is representative of those examples where determination of persistence is desired after emissions have ceased entering the environment (Mackay, 1979). This method could also be used to determine whether seasonal variation of plant growth significantly affects the uptake capacity of air pollutants by plants.

Inclusion of Vegetation in Multi-Compartment Modeling

Traditionally, most environmental models have ignored the vegetation compartment for several reasons. The uptake is believed to be small compared to other compartments; however, few experiments have measured uptake and the kinetics and equilibria of plant uptake is poorly understood. As the importance of vegetation as a route of exposure to toxic chemicals is understood, more models are incorporating the compartment. In addition to an exposure pathway, plants induce water movement from soil to atmospheres, stimulate microbial growth at the root zone increasing the degradation rate in the soil compartment, and take up contaminants within the air compartment (Mackay, 2001). This section summarizes developments in vegetation fugacity-based models.

It is not obvious how plant parts (e.g. roots, stem) should be combined or segmented into compartments. Three studies have illustrated the opportunity to integrate vegetation into fugacity models. In a study aimed at assessing the uptake of organic chemicals from air, the plant was separated into three compartments: leaf, stem, and root (Hung and Mackay, 1997). It was concluded based on comparison with analytical results that the model could generate accurate estimations without extensive physiological data. As the transport values (Dij), fluxes (Ni), and fugacities (fi) are similar for the stem, root, and hydroponic solution compartments, combining the three compartments could simplify the model. A simplified three-compartment model (air, foliage, soil with root) was developed by Cousins and Mackay (2001) and compared 12 non-ionic organic chemicals with varied physical-chemical properties. They concluded that those chemicals taken up by atmospheric deposition and transpiration through the plant roots are most likely affected by the vegetation compartment (Cousins and Mackay, 2001). A similar approach was used by Severinsen and Jager (1998) for a terrestrial vegetation model (SimpleBox, a multi-media model) to investigate the fate of xenobiotics at the regional scale. They found that the vegetation compartment influenced the soil concentrations of dimethoat, hexachlorobenzene, and bromacil, and that harvesting of vegetation was a significant fate process (Severninsen and Jager, 1998).

2.7. Knowledge Gaps, Research Goal, and Objectives

While research has shown that reactive nitrogen species deposit onto plant leaves and that vegetation can take up nitrogen dioxide from the air, the scaled impact on inorganic atmospheric emissions in general and the electric utility emissions in particular is largely unexplored. Additionally, it is understood that vegetation affects the partitioning of organic pollutants into the environment, yet the effects of vegetation on inorganic pollutant partitioning is not well understood. As initiatives develop that encourage curtailing of carbon (globally), mercury (nationally), and NO_X/SO_2 (regionally) through market-based approaches, determining the mitigating ability of plants in urban areas becomes increasingly important. Further, as green roofs represent diffuse emissions sinks, rather than emissions mitigation technology at the source, there is a challenge to explore the market potential and financial opportunities of the technology for the contaminant sources (i.e. the energy sector). The development of a quantitative and probabilistic framework for assessing of the fate of these contaminants in green roofs systems will provide a first step to quantify their economic impact, and to explore possible policy designs for their integration in clean air policies.

The goal of this project is to develop an engineering analysis-based policy tool for green roofs as a pollution abatement technology. The governing hypothesis for this research is that the business case for green roofs can be made by the integration of green roofs as a pollution abatement technology into an emissions market scenario.

The following three objectives are envisioned:

1. A screening-level meta-analysis of economic and environmental benefits from green roofs. The assessment of economic sensitivities to these benefits will provide boundary conditions for the integration of green roofs as a mitigation technology into an air emission market-based program;
2. Development and analysis of a fugacity-based fate and transport model to deterministically and probabilistically describe the fate of air pollution within a green roof system. Nitrogen oxide emissions from electric utility generators will be used as a proxy for a broader range of pollutants and to prototype the model feasibility. The outcome of this model will serve to calibrate the meta-analysis, and provide a quantitative assessment of green roof process and design parameters;
3. An analysis of current green roof policy, existing stormwater policy, and clean air policy to assess the potential for integrating green roofs into existing policies via market-based approaches. The necessary price of emission allowances that is required to make the economic case for green roofs will be determined.

Figure 2.11 summarizes the overall approach and shows how the three objectives interconnect and build upon each other.

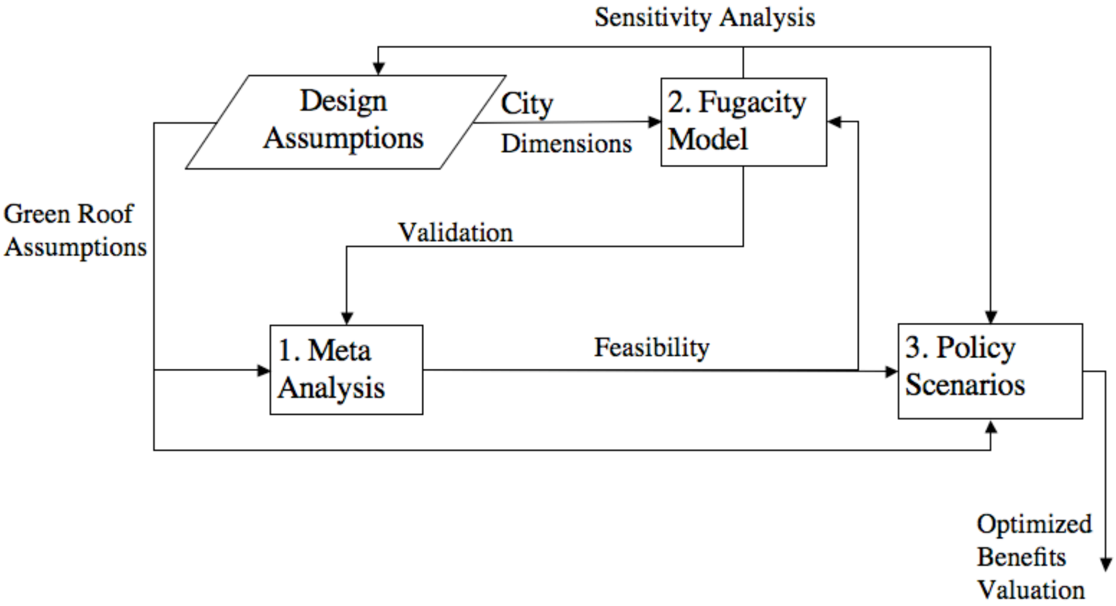


Figure 2.11 Diagram of research path.

Chapter 3

Methods

This section describes the methods that were adopted or developed to test the hypothesis, and address each objective.

3.1. Net Present Value Analysis

This section summarizes the economic analysis approach used to compare the cost-benefit analysis of a green roof and a conventional roof at the building-scale. A net present value (NPV) analysis prices the cost of future goods in terms of today's dollars. In the case of a green roof and a conventional roof, NPV allows for a comparison between the total cost of each system over a fixed time period. The following chapters detail the periods over which NPVs were calculated, to a maximum of 40 years, based on the assumption that the green roof lasts at least twice as long as a conventional roof. The net present value accounts for inflation and discounting in the following equation:

$$NPV = \sum_{n=0}^{N} FV \frac{\left(1 + i_{\text{inflation}}\right)^n}{\left(1 + i_{\text{discount}}\right)^n} \tag{3.1}$$

where FV is the future value, n is the number of years, i is the interest rate accounting for annual inflation and annual discounting.

It is assumed that the green roof lasts twice as long as a conventional roof due to the added protection to the waterproof membrane that the soil media provides (Köhler, 2006). Accounting for annual costs and benefits, the NPV for the green roof system is shown below:

$$NPV = Install + \sum_{n=0}^{N} \left(AnnualCosts \right) \frac{\left(1 + i_{\text{inflation}}\right)^{n}}{\left(1 + i_{\text{discount}}\right)^{n}} \tag{3.2}$$

For the conventional roof system, which requires a roof replacement at a future date, the equation becomes:

$$NPV = Install + \sum_{n=0}^{N} \left(AnnualCosts \right) \frac{\left(1 + i_{\text{inflation}}\right)^{n}}{\left(1 + i_{\text{discount}}\right)^{n}} + (Install) \frac{\left(1 + i_{\text{inflation}}\right)^{\left(\frac{1}{2}N\right)}}{\left(1 + i_{\text{discount}}\right)^{\left(\frac{1}{2}N\right)}} \tag{3.3}$$

The incorporation of annual costs and benefits allows for a comparison between the two NPV from year 0 to year *n*. As a result, one can determine at what year *n* the NPV of the green roof is equal to the NPV of the conventional roof in addition to observing the final NPV of the roof systems at year 40.

3.1.1. Propagation of Uncertainty

As the data for the net present value analysis are aggregated from separate sources with both normal and lognormal distributions, accounting for uncertainty requires determining the variance for both normal and lognormal distributions. For this analysis (as the data came from separate sources), it was assumed that there is no correlation between parameters (each parameter is independent). This allows the variances to be summed. For normal distributions, the expected value or mean, μ, is determined by

$$\mu = \frac{1}{N} \sum_{i=1}^{N} x_i \tag{3.4}$$

where N is the number of values and x_i is a value within the set X, is used to determine the variance. The equation for variance, σ^2, is then:

$$\sigma^2 = \frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2 \tag{3.5}$$

For a distribution of roof cost per unit area, multiplying the mean unit cost by a total roof area constant, *a*, affects the variance in the following way:

$$\sigma^2 = \frac{\sum(ax - a\mu)^2}{N} = a^2\frac{\sum(x-\mu)^2}{N} \tag{3.6}$$

The equations are somewhat different for two-parameter lognormal distribution (Johnson and Kotz, 1970). If X is the set of x_i values, X can be defined as:

$$U = \gamma + \delta\ln(X - \theta) \tag{3.7}$$

where γ, δ, θ are parameters. These parameters are related to the expected value (ζ) and standard deviation, σ, of Z, the natural log of X, according to the following equations:

$$\zeta = {}^{-\gamma}\!/_{\delta} \tag{3.8}$$

$$\sigma = \delta^{-1} \tag{3.9}$$

where ζ and σ are determined from Z=ln(X).

If θ is assumed to be zero, substituting ζ and σ into the equation yields:

$$U = \frac{(\ln(X) - \zeta)}{\sigma} \tag{3.10}$$

The first moment of this function is the expected value for a lognormal distribution:

$$\mu_1 = e^{\left(\zeta + \frac{1}{2}\sigma^2\right)} \tag{3.11}$$

The second moment of the function is the variance for a lognormal distribution:

$$\mu_2 = e^{2\xi} e^{\sigma^2} \left(e^{\sigma^2} - 1 \right) \tag{3.12}$$

To integrate the uncertainty into the net present value analysis, the variances of each distribution are summed according to:

$$Var\left(\sum \alpha_i x_i \right) = \sum \alpha_i^2 Var(x_i) \tag{3.13}$$

where α_i is the fractional contribution of the parameter to the future value (Johnson and Kotz, 1970). For example, if the future value (FV) is equal to:

$$FV = A + B + C \tag{3.14}$$

Then, the fractional contribution of A would be:

$$a_A = \frac{A}{FV} \tag{3.15}$$

The variance for the future value assuming a year greater than the present year, n>0, would be:

$$Var\left(\sum \alpha_i x_i \right) = a_A{}^2 \cdot \left(\sigma_A^2 \right) + a_B{}^2 \cdot \left(\sigma_B^2 \right) + a_C{}^2 \cdot \left(\sigma_C^2 \right) \tag{3.16}$$

The above equation describes the variance for a specific year. For the net present value, each year's variance would then be multiplied and divided by the square of the inflation and discount factors respectively.

3.2. Environmental Fate Fugacity-Based Model

Probabilistic fugacity-based fate and transport models will provide a robust and scalable quantitative assessment of the potential of air pollution mitigation to inform engineering analysis-based policy development.

A fugacity-based model was chosen as it allows for the incorporation of all system compartments, and for testing the impact of physical-chemical characteristics of a range of contaminant classes. Fugacity-based fate and transport models have been used to quantify contaminant partitioning into vegetation (mainly based on hydrophobic contaminants) (Severinsen and Jager, 1998; Cousins and Mackay, 2001). This method will be used to quantify uptake capacity of green roofs and yield information on potential stormwater impacts by atmospheric-born contaminants running off the roof.

The custom-designed fugacity-based model, SEDUM (Sequestering Emissions: a Designable Uptake Model) describes the green roof system through three compartments, air, soil, and vegetation. SEDUM is based upon Level III (Version 2.80) Model by the Canadian Environmental Modelling Centre (CEMC). The level III framework assumes steady-state conditions but does not assume equilibrium between the environmental compartments. The CEMC model is a six-compartment environmental model that includes air, soil, water, sediment, suspended sediment, and aquatic biota (CEMC, 2004). As SEDUM describes a green roof system, the sediment, suspended sediment, and aquatic biota compartments are not applicable. Additionally, a vegetation compartment was added and changes to the soil compartment were made to account for the green roof. The vegetation compartment while traditionally ignored in fugacity modeling has been adapted to a limited extent due to the complexities of the transport processes within vegetation. Figure 3.1 provides a schematic of SEDUM.

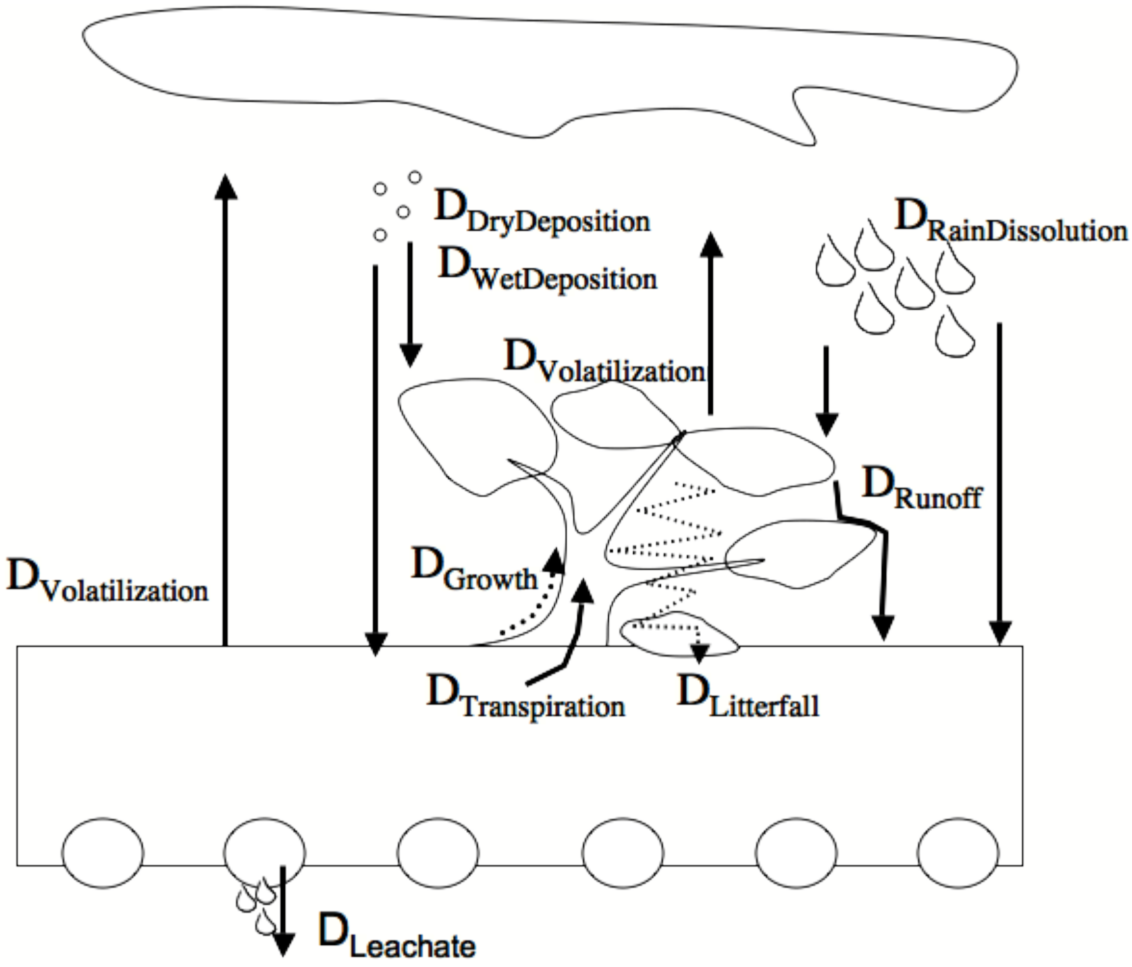


Figure 3.1 Schematic of SEDUM. Arrows represent major intermedia transport pathways incorporated in SEDUM. Not shown are the reactive losses within each compartment and advection into and out of the air compartment.

In SEDUM, water and aerosols are used to model atmospheric deposition to the vegetation and soil compartments, and are assumed to have a volume of zero for compartment modeling (Cousins and Mackay, 2001; Hung and Mackay, 1997; Severinsen and Jager, 1998). Due to this assumption, SEDUM provides contaminant concentration information for stormwater runoff rather than for a larger surface water compartment.

3.2.1. SEDUM: A Modified Level III Fugacity Model

Level III fugacity calculations account for the advective and diffusive transport that may occur between environmental compartments. The intermedia transfer equations are contained within a D value. While the fugacity approach will yield the same results as other concentration-based models if the transport expressions are equivalent, the benefit to using the fugacity approach is the complexity and detail that is contained within the D values and the ease at which D values can be compared to one another. What follows is a detailed explanation of D values equations used in the development of SEDUM. It is important to recognize that the D value for transfer from air to soil will most likely not be the same as the D value for movement from soil to air. While diffusive processes are identical in either direction, advective processes may move in only one direction (e.g. wet deposition). Further detail on these equations can be found in a series of papers on fugacity models (Mackay, 1979; Mackay and Paterson, 1981; 1982; Mackay et al., 1985) and in *Multimedia Environmental Models: The Fugacity Approach, 2nd edition* (Mackay, 2001). See the List of Symbols in the front of this dissertation.

Definition of Environment

To begin, the boundaries of the system under analysis should be defined. In describing the physical environment, the number of compartments is first determined (three for the purposes of this research: air, soil, and vegetation). From this, the volumes of the compartments, composition of the compartments (i.e. presence of aerosols in the air compartment), and general climatic information (e.g. wind speed, rain rate, temperature) are included.

Definition of Z Values

$$Z_{Air} = \frac{1}{RT} \tag{3.17}$$

$$Z_{Water} = \frac{1}{H} = \frac{C^S}{P^S} = \frac{Z_{Air}}{K_{AW}} \tag{3.18}$$

$$Z_{Octanol} = Z_{Water} K_{OW} \tag{3.19}$$

$$Z_{Soil} = y_{OC} K_{OC} Z_{Water} \left(\frac{\rho_S}{1000} \right) \tag{3.20}$$

where

$$K_{OC} = 0.41 K_{OW} \tag{3.21}$$

$$Z_{Aerosol} = Z_{Air} K_{QA} \tag{3.22}$$

where

$$K_{QA} = \frac{6 \cdot 10^6}{P_L^S} = y_{OM} K_{OA} \left(\frac{\rho_Q}{1000} \right) \tag{3.23}$$

Transport Equations

Advective transport occurs in the air compartment according to the following equation:

$$D_{AdvAir} = G_{Air} Z_{Air} \tag{3.24}$$

Reactive losses occur in all three compartments according to the following equations:

$$D_{RxnAir} = V_{Air} Z_{Air} k_{Air} \tag{3.25}$$

$$D_{RxnSoil} = V_{Soil} Z_{Soil} k_{Soil} \tag{3.26}$$

$$D_{RxnVegetation} = V_{Vegetation} Z_{Vegetation} k_{Vegetation} \tag{3.27}$$

Air-Soil Interface

Processes affecting transfer between the air and soil compartments include diffusion, rain dissolution, wet deposition, and dry deposition. The overall air-soil intermedia transfer equation is

$$D_{AirSoil} = D_E + D_{RWS} + D_{QWS} + D_{QDS} \tag{3.28}$$

where D_E, diffusion, is

$$D_E = \left[\frac{1}{k_{EA} \cdot A_S \cdot Z_{Air}} + \frac{Y_S}{A_S\left(B_{EA} \cdot Z_{Air} + B_{EW} \cdot Z_{Water}\right)}\right]^{-1} \tag{3.29}$$

where B_{EA} is

$$B_{EA} = B_{MA} \cdot \frac{v_A^{10/3}}{\left(v_A + v_W\right)^2} \tag{3.30}$$

$$B_{EW} = B_{MW} \cdot \frac{v_W^{10/3}}{\left(v_A + v_W\right)^2} \tag{3.31}$$

D_{RWS}, rain (wet) dissolution, is

$$D_{RWS} = A_S \cdot U_R \cdot Z_{Water} \tag{3.32}$$

D_{QWS}, wet particle deposition, is

$$D_{QWS} = A_S \cdot U_R \cdot Q \cdot v_Q \cdot Z_{Aerosol} \tag{3.33}$$

D_{QDS}, dry particle deposition, is

$$D_{QDS} = A_S \cdot U_Q \cdot Q \cdot v_Q \cdot Z_{Aerosol} \tag{3.34}$$

As advective processes only occur from air to soil, the overall soil-air intermedia transfer equation includes diffusion

$$D_{SoilAir} = D_E \tag{3.35}$$

Air-Vegetation Interface

To model potential uptake by the vegetation compartment, an addition to the CEMC model, it will be assumed that the fugacity capacity of the foliage is proportional to the fugacity capacity of octanol assuming a volume fraction of octanol-like material (Cousins and Mackay, 2001). The lipid partitioning assumption allows for a reasonable proxy for combined cuticular/stomatal uptake.

The equations for the assumption are below:

$$Z_{\text{Vegetation}} = v_{\text{FO}} Z_{\text{Octanol}} \tag{3.36}$$

$$Z_{\text{Octanol}} = Z_{\text{Air}} K_{\text{OA}} \tag{3.37}$$

where, v_{FO} is the volume fraction of octanol-like material in the vegetation, Z_{Octanol} is the fugacity capacity of octanol, Z_{Air} is the fugacity capacity of air, and K_{OA} is the octanol-air partitioning coefficient. This assumption allows the model to observe the potential uptake of plants without relying on plant-specific physiology data, as the data set on plant species is limited. An additional assumption for the vegetation compartment is that the rate of litterfall is equal to the growth rate of the plant (Cousins and Mackay, 2001). This assumption further removes seasonal variability from the model.

Processes affecting transfer between the air and vegetation compartments include the processes previously discussed in air and soil exchange: diffusion, rain dissolution, wet deposition, and dry deposition. Additionally, there is dry gaseous deposition and evaporation occurring at the surface of the vegetation. The overall air-vegetation intermedia transfer equation is

$$D_{\text{AirVegetation}} = D_{\text{GDV}} + D_{\text{RWV}} + D_{\text{DPV}} + D_{\text{WPV}} \tag{3.38}$$

where D_{GDV}, gaseous deposition to vegetation, is

$$D_{GDV} = \left[\frac{1}{D_C} + \frac{1}{D_B}\right]^{-1} \tag{3.39}$$

D_C, cuticle diffusion is defined by

$$D_C = A_S \cdot L \cdot U_C \cdot Z_{Vegetation} \tag{3.40}$$

U_C, is related to cuticle permeance, P_C, and K_{AW} by

$$U_C = 3600 \cdot P_C \cdot \frac{1}{K_{AW}} \tag{3.41}$$

with P_C related to K_{OW} via the following equation

$$\log P_C = \frac{\left(0.704 \cdot \log K_{OW} - 11.2\right) + \left(-3.47 - 2.79 \cdot \log MM + 0.970 \cdot \log K_{OW}\right)}{2} \tag{3.42}$$

D_B, boundary layer diffusion is defined as

$$D_B = A_S \cdot L \cdot U_B \cdot Z_{Vegetation} \tag{3.43}$$

D_{RWV}, rain (wet) dissolution to vegetation, is

$$D_{RWV} = FrUF \cdot U_R \cdot A_S \cdot Z_{Water} \tag{3.44}$$

where FrUF is the fraction of rain that is intercepted by the foliage of the vegetation.

D_{DPV}, dry particle deposition to vegetation, is

$$D_{DPV} = A_S \cdot U_D \cdot v_Q \cdot Z_{Aerosol} \tag{3.45}$$

D_{WPV}, wet particle deposition to vegetation, is

$$D_{WPV} = FrUF \cdot U_R \cdot A_S \cdot Q \cdot v_Q \cdot Z_{Aerosol} \tag{3.46}$$

Transfer from vegetation to air is limited to gaseous evaporation, which is assumed to be equal to the rate of dry gaseous deposition, D_{GDV}, as it is limited by diffusion through the leaf cuticles and boundary layer diffusion.

$$D_{VegetationAir} = D_{GDV} \tag{3.47}$$

Vegetation-Soil Interface

For transfer between the vegetation and soil compartments, exchange occurs via water runoff from vegetation to soil, litterfall to soil, and from soil via plant roots. Losses occur through plant growth as well. The total vegetation-soil intermedia transfer is

$$\mathrm{D_{VegetationSoil} = D_{Runoff} + D_{Litterfall} - D_{Growth}} \tag{3.48}$$

where $\mathrm{D_{Runoff}}$ is

$$\mathrm{D_{Runoff} = \left(1 - FruF\right) \cdot \left(D_{RWV} + D_{WPV}\right)} \tag{3.49}$$

$\mathrm{D_{Litterfall}}$ is dependent on the residence time of the foliage, the volume fraction of the vegetation, and the fugacity capacity of the vegetation.

$$\mathrm{D_{Litterfall} = \frac{1}{t_V} \cdot v_V \cdot Z_{Vegetation}} \tag{3.50}$$

For a steady-state analysis, we assumed that litterfall is equal to growth rate

$$\mathrm{D_{Litterfall} = D_{Growth}} \tag{3.51}$$

The Soil-Vegetation overall transfer equation is limited to root uptake

$$\mathrm{D_{SoilVegetation} = Tr \cdot A_S \cdot L \cdot TSCF \cdot Z_{Water}} \tag{3.52}$$

TSCF is dependent on $\mathrm{K_{OW}}$ according to

$$\mathrm{TSCF} = 0.784 \cdot e^{\left(-\left(\log \mathrm{K_{OW}} \cdot 1.78\right)^2 / 2.44\right)} \tag{3.53}$$

Stormwater “Compartment” Estimation

As the green roof is designed for water to percolate through the soil media before discharging off the roof, the standard method for surface water runoff is not appropriate for this system. Instead, a leaching rate represents the rainfall that is not transpired. According to Mackay (2001), the advective leaching value, D_L, is

$$D_L = G_L Z_W = \left(A_S\left(U_R - Tr\right)\right)Z_W \qquad (3.54)$$

This relationship assumes that the concentration of reactive nitrogen species in the water that runs off the green roof system is in equilibrium with the concentration in the water that remains in the soil media on the green roof (Mackay, 2001).

Multiple Chemical Species Analysis

As there are numerous reactive nitrogen species in the troposphere, the inclusion of multiple species will more completely account for pathways of transfer between the compartments in SEDUM. See Figure 3.2 for a summary of the complex reactions and transformations of nitrogen oxides in the troposphere.

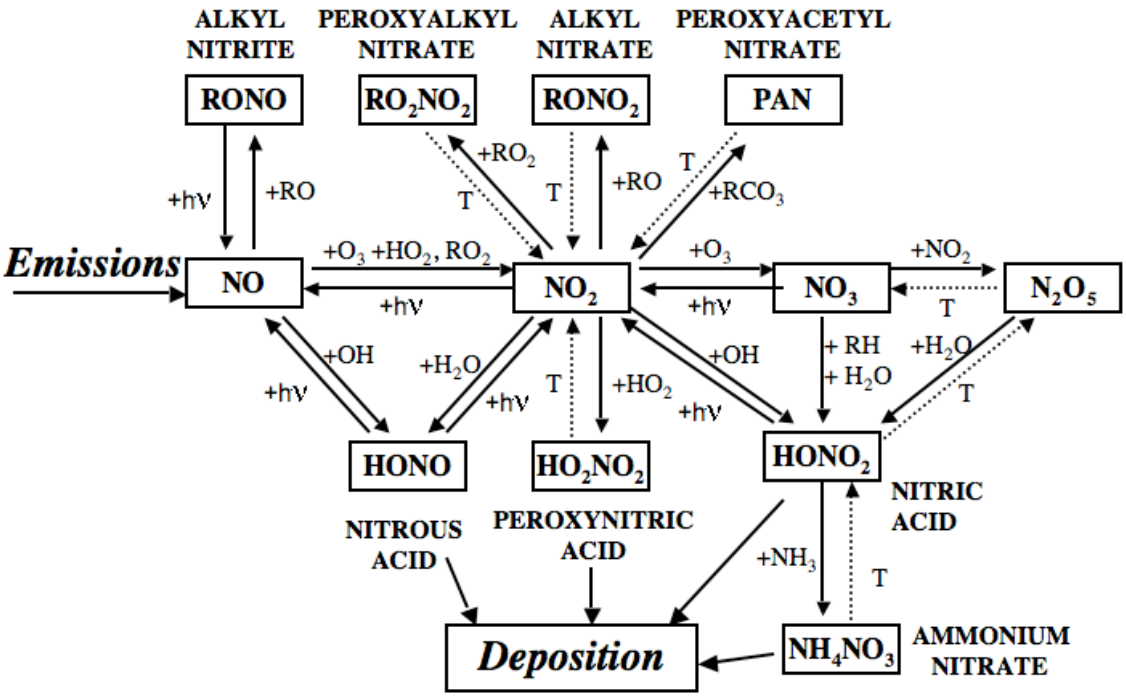
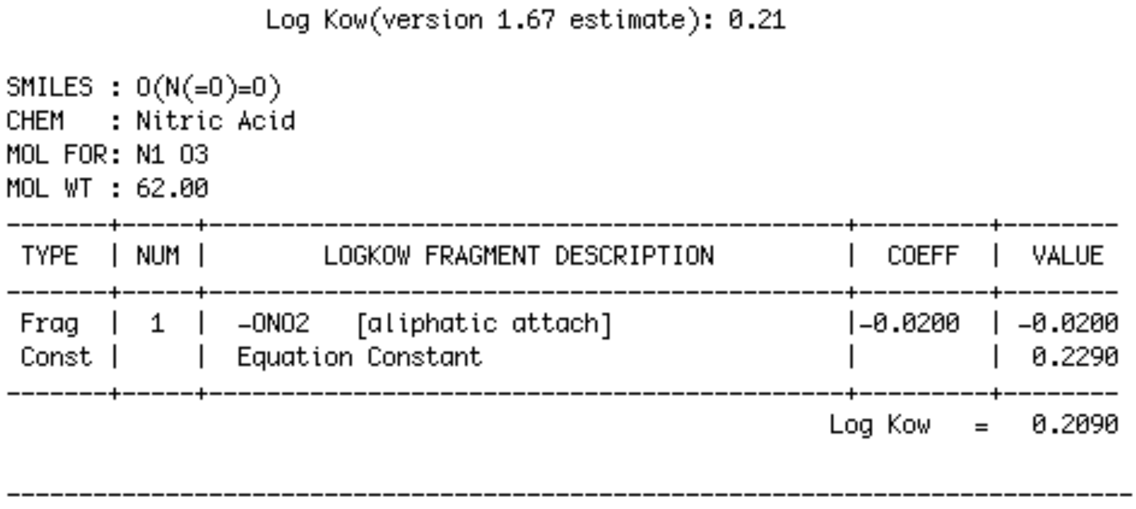


Figure 3.2 Transformations of reactive nitrogen species in the troposphere (adapted from Carroll, 2006).

Of the reactive nitrogen species in Figure 3.2, NO, NO_2, and HNO_3 (nitric acid) were selected for SEDUM. The methodology for multiple chemical species is adopted from Toose and Mackay (2004).

The model inputs and outputs will be adopted for the selected reactive nitrogen species (NO, NO_2, HNO_3), to obtain the relative concentration ratios of species within each transfer equation. First the model is parameterized using physical-chemical property data to acquire the appropriate fugacity capacities. The physical-chemical properties were obtained from the literature and from EPI (Estimations Programs Interface) Suite (EPA, 2007a). KOWWIN was the specific model within EPI Suite that was used to obtain estimates for the octanol-water partition coefficient for the selected species; the output is shown in Figure 3.3, Figure 3.4, and Figure 3.5.

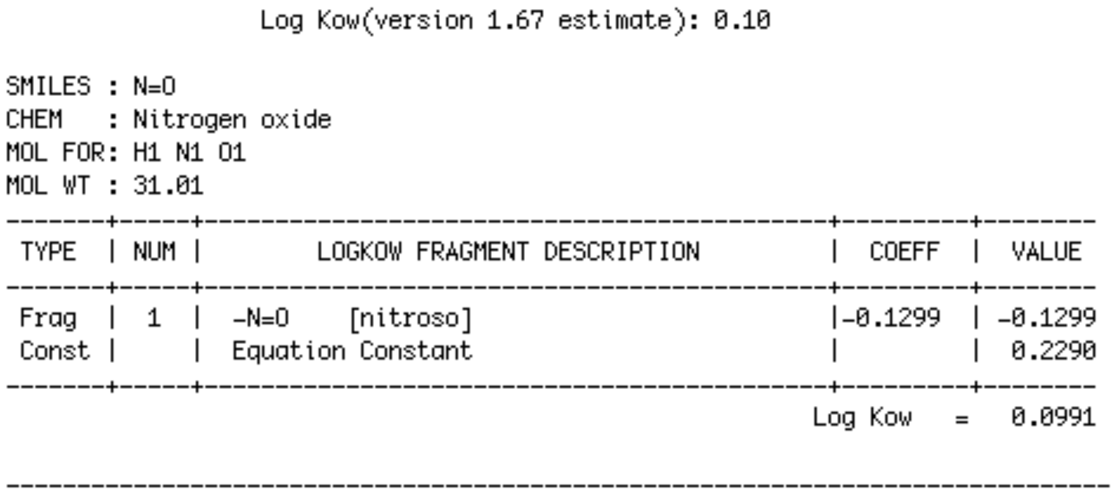


```
                  Log Kow(version 1.67 estimate): 0.21

SMILES : O(N(=O)=O)
CHEM   : Nitric Acid
MOL FOR: N1 O3
MOL WT : 62.00
-------+-----+--------------------------------------------+---------+--------
 TYPE  | NUM |        LOGKOW FRAGMENT DESCRIPTION         |  COEFF  |  VALUE
-------+-----+--------------------------------------------+---------+--------
 Frag  |  1  |  -ONO2   [aliphatic attach]                |-0.0200  | -0.0200
 Const |     |  Equation Constant                         |         |  0.2290
-------+-----+--------------------------------------------+---------+--------
                                                          Log Kow   =   0.2090

------------------------------------------------------------------------------
```

Figure 3.3 EPI Suite output for nitric acid.

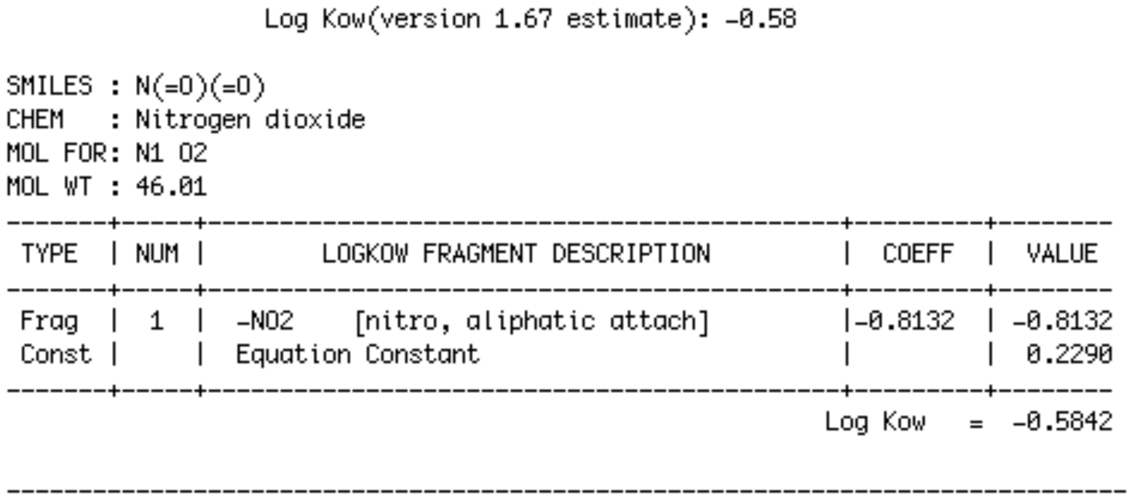


```
                  Log Kow(version 1.67 estimate): 0.10

SMILES : N=O
CHEM   : Nitrogen oxide
MOL FOR: H1 N1 O1
MOL WT : 31.01
-------+-----+--------------------------------------------+---------+--------
 TYPE  | NUM |        LOGKOW FRAGMENT DESCRIPTION         |  COEFF  |  VALUE
-------+-----+--------------------------------------------+---------+--------
 Frag  |  1  |  -N=O    [nitroso]                         |-0.1299  | -0.1299
 Const |     |  Equation Constant                         |         |  0.2290
-------+-----+--------------------------------------------+---------+--------
                                                          Log Kow   =   0.0991

------------------------------------------------------------------------------
```

Figure 3.4 EPI Suite output for nitrogen oxide.



```
                 Log Kow(version 1.67 estimate): -0.58

SMILES : N(=O)(=O)
CHEM   : Nitrogen dioxide
MOL FOR: N1 O2
MOL WT : 46.01
-------+-----+--------------------------------------------+---------+--------
 TYPE  | NUM |        LOGKOW FRAGMENT DESCRIPTION         |  COEFF  |  VALUE
-------+-----+--------------------------------------------+---------+--------
 Frag  |  1  | -NO2     [nitro, aliphatic attach]         |-0.8132  | -0.8132
 Const |     | Equation Constant                          |         |  0.2290
-------+-----+--------------------------------------------+---------+--------
                                                    Log Kow   =  -0.5842

---------------------------------------------------------------------------
```

Figure 3.5 EPI Suite output for nitrogen dioxide.

Empirical data were obtained for concentration ratios within each environmental compartment. As HNO_3 is the principle deposition pathway (Meyers et al, 1991), it was selected as the key species for the model. The concentrations of the other two compounds (NO and NO_2) were calculated based on the fugacities of HNO_3 and their relative ratios in each environmental compartment. Table 5.3 in Chapter 5 lists the range of values for concentrations and half-lives used in developing these ratios. Once the fugacity capacities and the concentration ratios are known, the fugacity ratios can be calculated.

$$\frac{f_2}{f_1} = \frac{c_2 / z_2}{c_1 / z_1} = \frac{c_2}{c_1} \cdot \frac{z_1}{z_2} \tag{5.55}$$

For diffusion in series or parallel, the intermedia transfer (D) values must first be calculated for each multiresistance process for each species prior to calculation of the ratios. These fugacity ratios were integrated into the rate equations as shown below.

$$Q = f_1 D_1 + f_2 D_2 + f_3 D_3 = f_1 D_1 \left(1 + \frac{f_2 D_2}{f_1 D_1} + \frac{f_3 D_3}{f_1 D_1} \right) \tag{5.56}$$

Substituting R_i for $f_i D_i/(f_1 D_1)$ simplifies the total rate equation

$$Q = f_1 D_1 \left(1 + \frac{f_2 D_2}{f_1 D_1} + \frac{f_3 D_3}{f_1 D_1} \right) = f_1 D_1 \left(1 + R_2 + R_3 \right) \tag{5.57}$$

The rate equation can be used for a single contaminant species by assuming R_2=R_3=0. The key species rate equation is then multiplied by the sum of the relative ratios of each species, R_T, which is incorporated into the compartment mass balance equations to determine the fugacity in each compartment.

Material Balance Equations

The intermedia transfer equations, advection equations, and reaction equations were all incorporated into SEDUM. The following three material balances were used to determine how nitrogen oxides would partition in a green roof system:

Air compartment

$$\begin{aligned} &\mathrm{E_A + G_A C_A + f_{Soil} D_{SoilAir} R_{TSoilAir} + f_{Vegetation} D_{VegetationAir} R_{TVegetationAir}} = \\ &\quad \mathrm{f_{Air} \left(D_{AirSoil} R_{TAirSoil} + D_{AirVegetation} R_{TAirVegetation} + D_{RxnAir} R_{TRxnAir} + D_{AdvAir} R_{TAdvAir} \right)} \end{aligned} \tag{5.58}$$

Soil compartment

$$\begin{aligned} &\mathrm{f_{Air} D_{AirSoil} R_{TAirSoil} + f_{Vegetation} D_{VegetationSoil} R_{TVegetationSoil}} = \\ &\quad \mathrm{f_{Soil} \left(D_{SoilAir} R_{TSoilAir} + D_{SoilVegetation} R_{TSoilVegetation} + D_L R_{TL} + D_{RxnSoil} R_{TRxnSoil} \right)} \end{aligned} \tag{5.59}$$

Vegetation compartment

$$\begin{aligned} &\mathrm{f_{Air} D_{AirSoil} R_{TAirSoil} + f_{Soil} D_{SoilVegetation} R_{TSoilVegetation}} = \\ &\quad \mathrm{f_{Vegetation} \left(D_{VegetationAir} R_{TVegetationAir} + D_{VegetationSoil} R_{TVegetationSoil} + D_{RxnVegetation} R_{TRxnVegetation} \right)} \end{aligned} \tag{5.60}$$

The above three equations have three unknown fugacities. The equations were transformed using Maple Version 11, a symbolic mathematics software program, to solve in terms of the fugacities (Maplesoft, 2007).

3.2.2. Sensitivity Analysis

Monte-Carlo type simulations were used to quantify the uncertainty associated with the input parameters, and to propagate the uncertainty throughout the model to create an output probability space. For the Monte-Carlo Analysis, the software, Crystal Ball 7, was used (Oracle, 2007). The software integrates with Microsoft Excel, and yields information on model sensitivity to parameter variation. Parameters evaluated include: roof area, solid matrix properties, regional climate and atmospheric contaminant concentration data, and contaminant classes (nitrogen oxides, sulfur dioxide, ozone, particulate matter, and volatile organic compounds).

3.3. Scenario Development to Assess Policy

To determine how green roofs fit into existing policies addressing environmental problems that plague cities, a regulatory review of stormwater and nitrogen oxide air emission trade programs was conducted as they pertain to cities meeting environmental goals. The review of stormwater regulations focused on the National Pollutant Discharge Elimination System (NPDES) permit requirements for Municipal Separate Storm Sewer Systems (MS4s) (EPA, 2002). Two market-based emission trade programs were reviewed for nitrogen oxides: the REgional CLean Air Incentives Market (RECLAIM) Program and the NO_X Budget Trade Program (AQMD Rule XX; 40 CFR, Chapter 1, Part 51).

The impact of various policies on the net present value of green roof systems was assessed via the development of three scenarios. The net present value of the conventional roof was compared to the green roof under the following scenarios:

> **Scenario 1**: Stormwater incentives under the NPDES MS4 program. Current green roof incentive strategies focus on stormwater fees. This scenario determined the annual required savings under such a system for the NPV of the green roof to be equal to the conventional roof within a private-sector decisionmaker's time horizon.
>
> **Scenario 2**: Assuming that green roofs could serve as an offset or qualify as a *best available control technology* (BACT) as defined under the RECLAIM program or the NO_X Budget Trade Program, there is an annual market value for the emissions avoided. This scenario determined the required market value in dollars per Mg_{NOX} for the NPVs to be equal within a private-sector decisionmaker's time horizon.
>
> **Scenario 3**: Combined the incentive strategies of Scenario 1 and Scenario 2 to evaluate a required market price for stormwater fee reductions and emission reductions if the policies were designed to work together to reduce the NPV of the green roof to that of the conventional roof within the time horizon of a private-sector decisionmaker.

To determine a necessary price of stormwater fees and nitrogen oxide allowances, each scenario was evaluated for a time horizon of 5 years, 10 years, and 20 years. These will be compared with the current price of stormwater fees and the current price of tradable permits for nitrogen oxides.

The following three chapters summarize the rationale and approach of these methods and discuss the results obtained via these methods.

Chapter 4

A Probabilistic Economic Analysis of Green Roof Environmental Benefits

4.1. Introduction

Urbanization increases stress on private and public utilities resulting in increases in the demand for energy, water and sewer services, and transportation (UN ESA, 2006). To meet increased energy demand, more than 150 new coal-fired power plants are proposed in the USA alone by 2030 with residential and commercial buildings currently contributing to 39 percent of energy consumption (Laboratory, 2006; Administration, 2007). Converting green space into neighborhoods, shopping malls, and other developments increases the need for infrastructure investment in storm sewer systems (SEMCOG, 2001). New road infrastructure leads to increased vehicle emissions, and along with parking lots and rooftops, roads contribute to elevated urban surface temperatures by reducing a city's albedo. Increased urban temperature, commonly referred to as the urban heat island effect (UHIE), in combination with emissions from the electric utility industry, impact local and regional air quality (Rosenfeld et al., 1995). As growth is inevitable, a multi-faceted and scalable solution is needed to temper the environmental impacts of growing cities. Increasingly, developers, architects, and city planners recognize that green (vegetated) roofs may be part of the solution. Composed of a drainage layer, a solid matrix "soil" layer, and vegetation, green roofs increase the insular capabilities of roofs and restore the water balance between evapotranspiration and runoff (Lazzarin et al., 2005).

Much of the research on green roofs focuses on the insulation capability during summer months, which reduces the flux of solar radiation in a building (Del Barrio, 1998). A study by Takebayashi and Moriyama (2007) on the surface heat budget of a green roof and a high reflectivity (white) roof revealed that both systems have a small sensible heat flux compared to a concrete roof surface. The small heat flux on the white roof is due to the low net radiation while that of the green roof was attributed to the large latent heat flux by evaporation (Takebayashi and Moriyama, 2007) .

There are two main parameters that influence the solar radiation reaching the roof deck, leaf foliage and soil media. The more extensive the foliage density of a particular plant, the more the heat flux through the roof decreases (Del Barrio, 1998; Theodosiou, 2003) and the greater the decrease in surface temperatures (Wong et al., 2003). Thick soil layers reduced cooling needs during summer months while thin substrate layers resulted in little to no cooling benefit (Theodosiou, 2003). Additionally, a dry environment and wind speed increase the rate of evapotranspiration, thereby aiding the absorbance of solar radiation by plants (Theodosiou, 2003). Generally, heat transfer is greater on roof surfaces that are not vegetated (Wong et al., 2003).

Green roofs retain as much as seventy percent of annual rainfall precipitation depending on regional climate (VanWoert et al., 2005). Rainfall retention is also affected by slope and substrate depth: in general, the flatter the roof, the greater the retention and peak flow reduction (VanWoert et al., 2005). While increased thickness provides increased storage capacity, moisture is also retained for a longer period of time limiting the effectiveness of retention for subsequent storm events. Villarreal and Bengtsson (2005) found that the moisture content of the media had a greater affect on peak flow and total stormwater volume reduction than slope (Villarreal and Bengtsson, 2005).

Green roofs exhibit the capacity to reduce pollution in urban environments from ground level ozone (Dousset and Gourmelon, 2003). Vegetation plays a role in lowering surface temperatures through latent heat removal from soils via evaporation and transpiration in the presence of high moisture levels (Taha et al., 1991). The absorption of incoming solar radiation by impervious surfaces creates an urban heat island where temperatures are elevated. Anthropogenic heat and pollution can further intensify the UHIE by creating an inversion layer, resulting in increased air conditioning demand (Rosenfeld et al., 1995), and heat-stressed related mortality and illness (Hogrefe et al., 2004).

With vehicular and power plant emissions, the reactive chemistry in urban areas can be greatly affected by nitrogen oxides. Nitrogen oxides (NO_X) alone or in combination with other air pollutants such as ozone, sulfur oxides, and particulate materials (PM) can cause respiratory diseases and increase the risk of heart attacks (Brunekreef and Holgate, 2002). Damage from NO_X can extend to plants as well reducing growth, respiration, photosynthesis, stomatal conductance, and enzyme activities (Wellburn, 1990). While no studies modeling the effects or removal of air pollutants by green roofs have been reported in the peer-reviewed literature, there is extensive work on the uptake of reactive nitrogen species by vegetation (Hanson and Lindberg, 1991).

Although green roofs have been shown to mitigate stormwater runoff volume and to reduce the heating and cooling loads of buildings, the challenges for widespread integration of green roofs include the premium cost over conventional roofs, and widely diverging municipal management practices for stormwater and air pollution control. For example, in the USA, the financial burden of managing stormwater is rarely applied to property owners according to area and intensity of impervious area. Reducing the uncertainty in the quantification of economic benefits of green roofs is a necessary first step to develop policies aimed at stimulating widespread acceptance of the technology in the United States.

The objective of this paper is to quantitatively integrate probabilistic ranges of stormwater, energy, and air pollution benefits in an economic model capturing the building-specific scale. A secondary goal is to assess the impact and opportunities of market-based air credit valuation as a policy tool for green roof diffusion.

4.2. Materials and Methods

The first step describes a cost-benefit analysis that can be applied to a range of green roof projects through a probabilistic evaluation procedure. This analysis provides information relevant to building owners, developers, and designers regarding the costs and environmental benefits (stormwater reduction, energy savings, and air quality) of green roof technology. This section summarizes the steps for the cost-benefit analysis at the building scale.

4.2.1. Installation Costs for Conventional and Green Roofs

To determine how the environmental benefits reduce the installation cost gap between green and conventional roofs, the magnitude of the gap was first determined. Cost and size data were obtained from re-roofing cost and time estimates provided by plant operations for seventy-five campus roofs from the University of Michigan in Ann Arbor, Michigan. Within this sample, the mean cost of a conventional flat roof was \$167 per m^2 (standard deviation: \$28 per m^2). The mean campus roof is 1870 m^2 and the mean building floor area is 9730 m^2.

The distribution of green roof installation costs was based on available green roof case data (Earth Pledge, 2005). As the price of green roofs can vary according to design and function (e.g. intensive green roof can serve as a garden), the cases used in the data analysis were limited to extensive roofs with a depth between 5 and 15 centimeters. The collected data represent the additional cost of the green roof components. The distributions of the conventional roof and green roof were summed to obtain the total cost of installation for a new green roof with a new conventional roof. The mean difference between the cost of the green roof and the conventional roof is defined as the cost gap. The internal rate of return was then determined for each environmental benefit.

4.2.2. Stormwater Fees and Reductions

The reduction of stormwater volume by green roofs benefits municipalities; however, not all local water authorities pass the economic savings on to the owner of the green roof. Traditionally, the budget for stormwater management is provided through property taxes or potable water use fees. In recent years, municipalities have been moving toward stormwater fees based upon total impervious surface on a property, creating an opportunity to “credit” green roofs for stormwater reduction. Two methods were used for determining stormwater fees and the reduced fee for a green roof. The first method is limited to the City of Ann Arbor, Michigan and its new stormwater ordinance. The commercial stormwater fee is \$279.10 per acre per quarter (\$0.28 per square meter per year) (City of Ann Arbor, 2007). The second method takes an average fee based on available data from eleven municipalities with established stormwater management fees (Table 4.1).

Table 4.1 Municipal stormwater fees per area of impervious surface.

City†	State	Annual Rate (2006\$/m^2)	Green Roof Benefit	Notes
Ann Arbor	MI	0.37	--	2006 Stormwater fees. New 2007 policy evaluated separately.
Atlanta	GA	0.08	--	Rate applies to Gwinnett County
Bellevue	WA	0.09-0.38	--	Varies according to degree of imperviousness.
Boulder	CO	0.06-0.08	--	Residential rates based on parcel size.
Gainesville	FL	0.35	--	
Minneapolis	MN	0.06-0.09	50%	50% reduction for control of 10-year, 24 hr storm. 100% for control of 100-yr, 24 hr storm.
Portland	OR	0.07	35%	35% fee reduction.
Seattle	WA	0.04-0.36	--	Varies according to degree of imperviousness.
Takoma	WA	0.21	--	
Washington	DC	0.03	--	Residential rate used.

†Sources listed in References according to city.

It was assumed that the reduction in stormwater fees due to a green roof is normally-distributed at fifty percent of the stormwater fee for the building footprint (City of Minneapolis, 2006).

4.2.3. Energy Savings Determination and Valuation

The energy savings were based on mixed-use administrative/laboratory buildings at the University of Michigan campus in Ann Arbor, Michigan. Total expenditures for energy (natural gas and electricity) consumption (mean $225,000), total energy consumption (mean 4050 MWh), and energy consumption by fuel source (mean 2370 MWh from electricity and 1670 MWh from natural gas) were obtained for 75 university buildings for fiscal year 2003. National commercial building energy consumption statistics provided additional data (e.g. average commercial conductance, system load factors) (Huang and Franconi, 1999). To determine the roof's contribution to the HVAC energy requirement, the heat flux through the roof was determined according to two methods.

The first method is based on EnergyPlus v2.0.0, a building energy simulation software program supported and made available by the US Department of Energy (US DOE, 2007). It can model building heating, cooling, lighting, ventilating, and other energy flows, based on climate and building use, material, and size inputs. Version 2.0.0, released in April 2007, contains the capability to include a green roof (referred to as *ecoroof*) on a building. The ecoroof component accounts for heat flux through a 1-dimensional heat transfer model. The model accounts for heat transfer processes within the soil and plant canopy, but it does not account for the soil moisture dependent thermal properties of the green roof (EnergyPlus Development Team, 2007).

The second method is a simplified 1-dimensional heat flux equation that assumes a R-value of 1.2 ft^2*^oF*h/Btu (conductance of 4.7 $W/m^2/K$) per centimeter depth for a 10.2-cm soil media of a green roof.

$$\dot{Q} = h \cdot A \cdot \Delta T = \frac{A \cdot \Delta T}{R}$$

where Q is the heat flux through the roof (W), A is the area of the roof (m^2), ΔT is the temperature difference between the building interior and the ambient temperatures (K), and h is the heat transfer coefficient ($W/m^2/K$). This coefficient is a function of the thermal conductivity of a material and the material thickness. The inverse of h is the R-value, which represents a material's resistance to heat flow. The larger the R, the less heat flux Q. In the construction industry, R-value ($ft^2 {*} {}^oF {*} h/Btu$) is commonly used to compare the effectiveness of insulation in building materials. For this method, an average R-value of 11.34 $ft^2 {*} {}^oF {*} h/Btu$ (conductance of 0.50 $W/m^2/K$) was assumed for the conventional roof according to national commercial building data (Huang and Franconi, 1999). The total combined R-value for a conventional roof with a green roof is 23.4 $ft^2 {*} {}^oF {*} h/Btu$ (total conductance of 0.24 $W/m^2/K$). The requisite energy consumption by the HVAC system to compensate for the loss through the roof was then determined. Annual totals for heat loss and cooling loss were multiplied by a system factor as suggested by Huang and Franconi (1999).

Energy costs due to the heat flux were determined assuming natural gas for heating and electricity for cooling. Pricing for energy was based upon available university energy expenditure information, \$0.08/kWh for electricity and \$0.02/kWh of natural gas. Heating and cooling degree-days were used for the R-value analysis, while hourly weather data was supplied for the EnergyPlus model (EnergyPlus Development Team, 2007a).

4.2.4. Air Quality Improvement and Valuation

Impact on air quality was limited to the mitigation of nitrogen oxide (NOx). Nitrogen oxide emission allowances are currently traded in the US; market-based economic valuations for 2005-2006 ranged from \$900 per ton (\$992 per Mg) to \$4,282 per ton (\$4,721 per Mg) (EPA, 2007; SCAQMD, 2007). To quantify nitrogen oxide uptake by plants (per unit area), data from Morikawa, et al. (1998) were used (Morikawa et al., 1998). That study evaluated the NO_X uptake potential of 217 plant taxa under controlled conditions in a greenhouse environment. Although sedums, the traditional vegetated roof plants of choice, were not evaluated, the study included a member of the same family, *Crassulaceae*. Published results were in terms of mg N g^{-1} dry weight per 8 hours of daylight exposure. The following assumptions were made to obtain the uptake capacity per unit area (kg_{NO2} m^{-2} y^{-1}): (i) Ninety percent of plant mass is water; (ii) Leaf thickness is 2 mm; (iii) Leaf area index (LAI) is 5 (m^2 leaf area per m^2 surface area); (iv) Average hours of daylight per day (twelve) (Severinsen and Jager, 1998). Calculations were performed to capture the potential impact of all 217-plant taxa on NO_X uptake. The distribution of uptake potentials (Figure 4.1) is assumed to be lognormal with a mean of 0.27 ± 0.44 kg_{NO2} m^{-2} y^{-1}. An implicit assumption was that the uptake capacity is constant on a year-to-year basis.

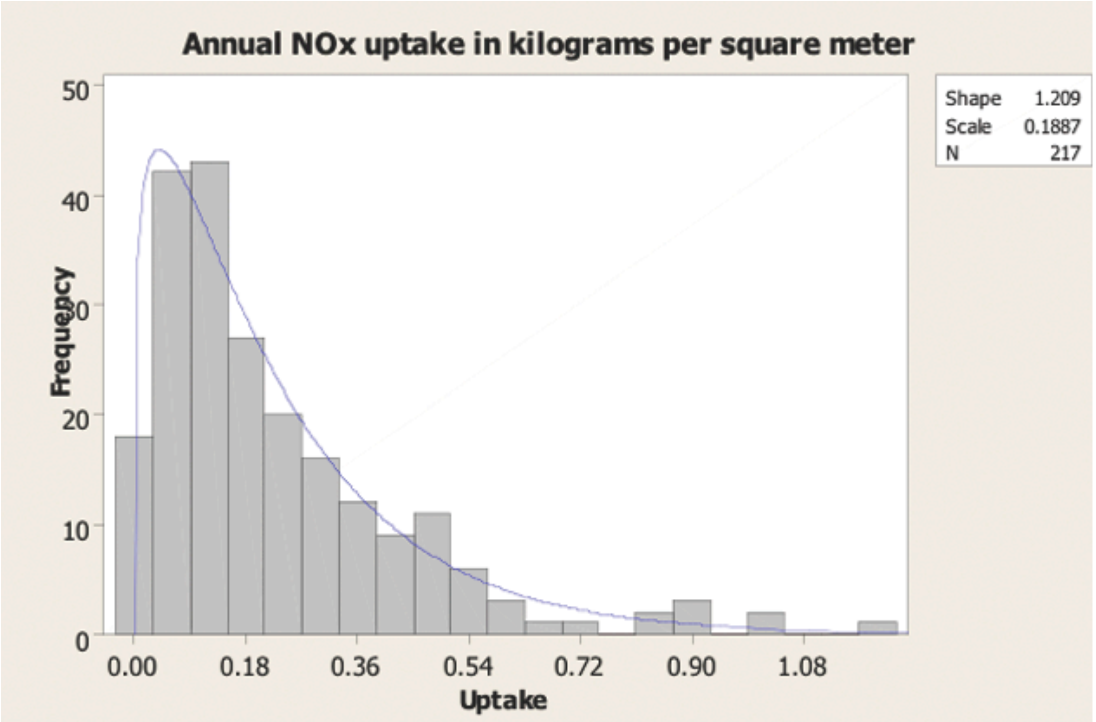


Figure 4.1 Distribution of nitrogen oxide uptake per area.

Once the annual uptake of NO_X was determined, the result was translated to health benefits. These calculations were based upon two estimation methods developed by the US Environmental Protection Agency (EPA) as part of a regulatory impact analysis of NO_X reductions in 1998 (US EPA, 1998). The conclusion of the analysis for the Eastern US, was that fewer premature deaths and fewer cases of chronic bronchitis translated into an economic benefit between \$1680 and \$6380 per Mg adjusted to 2006 dollars (US EPA, 1998). The two estimates were based upon the results of several atmospheric models that provided estimates for secondary ozone, nitrogen deposition, and particulate formation (US EPA, 1998). The range of economic benefit accounts for uncertainty in atmospheric acid sulfate concentration, which affects ammonium nitrate particulate formation (US EPA, 1998). For the purposes of this study, the estimates are referred to as the *low estimate* (\$1680 per Mg) and the *high estimate* (\$6380 per Mg). It should be noted that these values are in a similar range of emission allowance values.

4.2.5. Economic Analysis and Sensitivity Analysis

Once the costs and benefits were determined on a per unit area basis, the results were integrated into an economic model to determine the length of time required for a return on investment in a 2,000 m^2 green roof according to the net present values (NPV) of a green roof and conventional roof.

Conventional roof installation and replacement net present value

$$NPV_{conventional} = C_{installation} + \sum_{n=20,40} \frac{C_{replacement}}{(1+i_d)^n} \cdot (1+i_f)^n$$

Green roof installation net present value

$$NPV_{green\ roof} = C_{installation}$$

Net present value of benefits due to reduced stormwater fees

$$NPV_{stormwater} = \sum_{n} \frac{C_{stormwater}}{(1+i_d)^n} \cdot (1+i_f)^n$$

Net present value of benefits due to reduced energy consumption

$$NPV_{energy\ savings} = \sum_{n} \frac{C_{energy\ savings}}{(1+i_d)^n} \cdot (1+i_f)^n$$

Net present value of benefits due to improved air quality

$$NPV_{air\ pollution} = \sum_{n} \frac{C_{air\ pollution}}{(1+i_d)^n} \cdot (1+i_f)^n$$

where n is number of years, i_d is discount rate, and i_f is the inflation rate.

Figure 4.2 Equations used in the net present value analysis.

Figure 4.2 lists the equations used to determine the NPV. An interest rate of five percent (based upon the 2006, 20-year US government bond interest rate) and inflation rate of three percent (based upon the 2005 to 2006 Consumer's Price Index) were used (US Federal Reserve, 2006; US DOL, 2006).

It was assumed that the conventional roof would be replaced after twenty years (Köhler, 2006; ASCE, 2005). Maintenance costs have not been included in this analysis. Until plants are established (1-3 years), maintenance costs may be greater for a green roof. After establishment, expenses should be equal to or less than a conventional roof. A sensitivity analysis evaluated model sensitivity to economic parameters, climate factors, and variability in air pollution uptake.

4.3. Results and Discussion

The following summarizes the analysis. The implications of the benefits on city environmental policy are also discussed.

4.3.1. Stormwater Benefits

For the Ann Arbor assessment, a per square meter area cost was assumed (instead of the full cost for one acre). The stormwater fee for a conventional roof of 2,000 m^2 is then \$520 per year (City of Ann Arbor, 2007a). As Ann Arbor considers a green roof to be a pervious surface, then the green roof fee would be \$0 per year. The mean stormwater fee was found to be \$0.17/m^2 (standard deviation: \$0.12/m^2) (Resources 2007d; City of Bellevue 2006; City of Boulder; City of Gainesville 2006; County of Gwinnett 2006; City of Portland 2007; City of Seattle 2007; City of Minneapolis 2006; City of Tacoma 2006). Potential fee reductions for green roofs resulted in a mean stormwater fee of

\$0.08/m^2 (standard deviation: \$0.06/m^2). For the 2,000 m^2 roof, conventional roof fees would be \$340 while the green roof scenario would have fees of \$160 per year. A few municipalities offer fee reductions to green roof projects (assuming reduced impervious area and adequate storm capture) to pass the value of the public benefit of stormwater reduction to the building owner (e.g. Minneapolis, Minnesota) (City of Minneapolis, 2006).

4.3.2. Energy Assessment

The heat flux was based on a 2,000 m^2 roof utilizing hourly climate data from nearby Detroit, Michigan for the EnergyPlus simulation and heating and cooling degree days for Ann Arbor, Michigan for the R-value analysis. Roof conductance values and energy savings between conventional and green roof systems were different according to model method, and are summarized in Table 4.2.

Table 4.2 Roof conductance according to different energy models.

Roof type	Roof Conductance (W/m^2/K)		
	R-Value Model	EnergyPlus Model	ESP-r Model
Conventional	0.5	0.38	0.59 (45)
Green	0.24	0.36	0.42 (45)

A study by Saiz et al (Saiz et al., 2006) compared several roof systems for a roof in Madrid and the conductance of the roofs are provided in Table 4.2. The conductivity estimates for the conventional roof and green roof by Saiz et al (Saiz et al., 2006) is larger than the results from both models presented here. This may be due to their use of an existing building in Madrid, Spain for the analysis (age, different insulation requirements) and the assumption of pine bark and compost as the primary constituents of the soil media for the green roof, which would affect soil moisture properties. For the EnergyPlus analysis, the difference in consumption for a one floor commercial facility with a green roof versus a conventional roof is 16.4 MWh with 6.6 MWh saved from electricity and 9.8 MWh from heating. Based on energy costs for 2003 and adjusted to 2006 dollars (2003 energy expenditure data was available from the university and energy prices for 2004 and 2005 were unusually high), this translates to a savings of $710 of the green roof over the conventional roof. For the R-value analysis, there was a 66.1 MWh savings for the green roof with 59.5 MWh attributable to heating and 6.6 MWh for cooling. This translates to a savings of $1670 of the green roof over the conventional roof. While the two models agree on electricity savings, they differ in estimates for heating. The EnergyPlus model accounts for the other envelope heat loss pathways such as walls, windows, and slab, which have higher conductivities, 0.51, 3.25, and 2.69 respectively. When heat flux occurs, the EnergyPlus model suggests that greater losses would occur through these pathways than the roof. During periods of heating, the difference between interior and exterior conditions are greater than during periods of cooling, so the magnitude of error in heat flux between the models would be greater under conditions of heating than under cooling conditions. Uncertainty for these calculations is not included in the NPV analysis as the dependency on soil moisture and green roof soil media conductance has not yet been investigated in the literature.

To verify the appropriateness of the assumptions used in the analysis, calculated energy costs through the conventional roof were compared to actual expended total natural gas and electric energy costs for university buildings. Assuming that 35% of total building energy consumption is due to heating, ventilation, and air conditioning (HVAC) system use (D&R International, 2005), 90% of all buildings (75 total) were within the expected costs attributed to HVAC use. The eight buildings with higher energy expenditures had roof area-to-floor-space ratios much greater than one (R/F area >> 1). The ratio can be explained by the inclusion of roof areas outside the interior building floor area (e.g. exterior walkways, loading docks), including these areas in the heat flux calculations would overestimate contribution to the HVAC consumption.

4.3.3. Air Pollution Mitigation

The benefit assessment included both direct and indirect methods of uptake. The uptake capacity per area for the 217 plant taxa evaluated by Morikawa et al. (1998) had a mean of 0.27 $kg_{NO2}/m^2/y$ (variance: 0.17 $kg^2_{NO2}/m^4/y^2$). For a building with a roof area of 2000 square meters, this results in an uptake of 530 Mg_{NO2}/y (variance: 700 Mg^2_{NO2}/y^2). The public health benefits for greening a 2000 m^2 roof were determined to be $890 (variance: 2.0E6 $\$^2$) for the low benefit estimate and $3390 (variance: 2.8E7 $\$^2$) for the high benefit estimate.

For large-scale urban greening projects, it should be noted that not all of these roofs may be conducive to green roof implementation due to restrictive architectural features (e.g. roof slope, HVAC system placement, structural limitations of building). However, if greening occurred on all 35 ha of roofs evaluated in this study at the University of Michigan, potentially 94.31 Mg_{NO2}/y could be removed from the air annually with an estimated value to public health between $158,720 and $601,930 per year.

4.3.4. Net Present Value Analysis

The environmental benefit results were integrated into an economic model to determine the length of time required for a return on investment (ROI) for an individual building's green roof system. The mean green roof upfront cost is 39 percent higher than the conventional roof at installation ($464,000 versus $335,000). The NPV of the costs of the two roof systems was calculated using both energy estimates and stormwater estimates. The NPV of the green roof is between 20.3 and 25.2 percent less than the conventional roof over 40 years under the current methods (stormwater fees and energy savings) with the difference in calculation of energy savings accounting for greater variation than the difference in calculation of stormwater fee savings (Figure 4.3, Table 4.3).

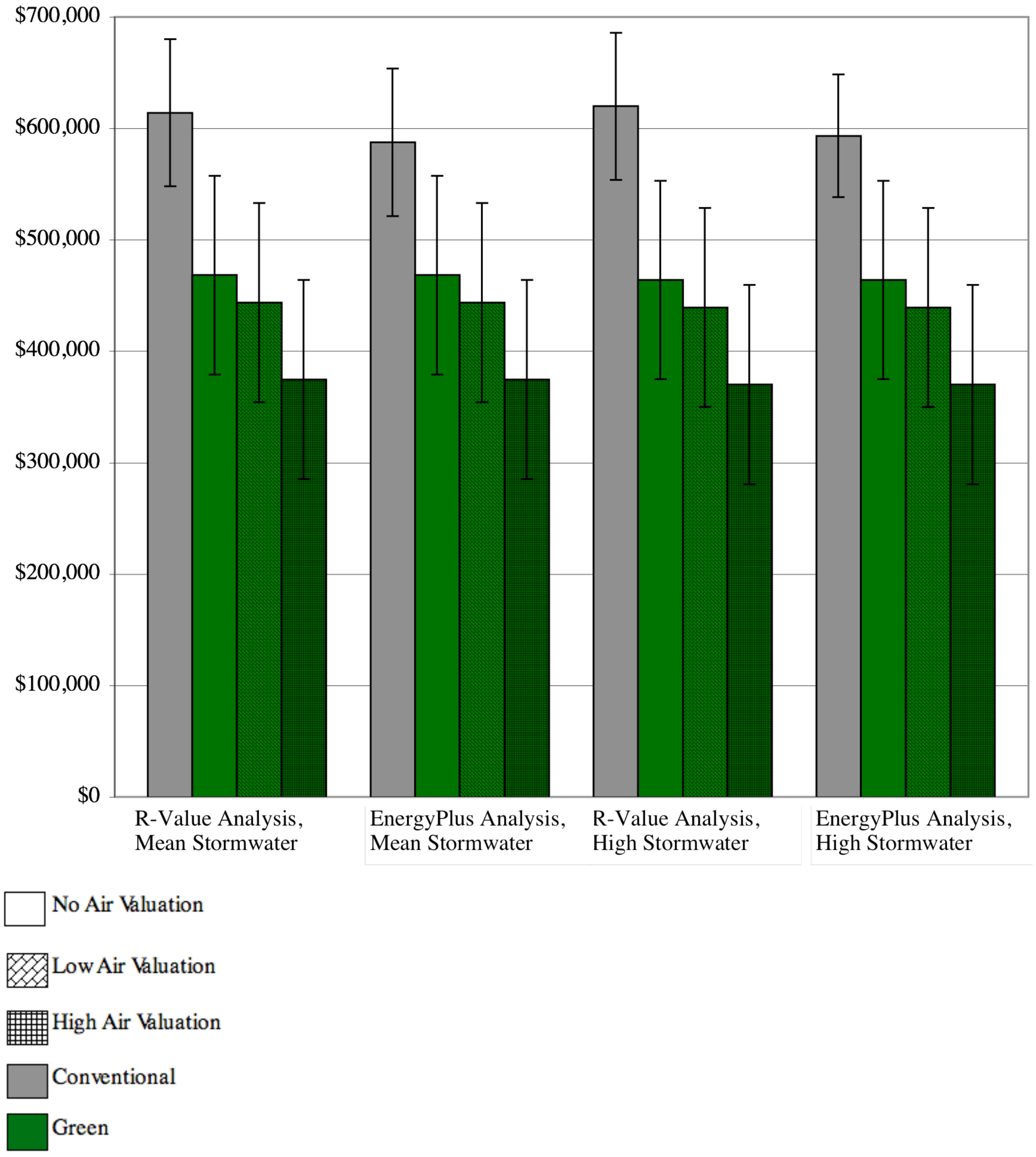


Figure 4.3 Net present value over 40 years for a conventional roof and a green roof under various valuation and modeling scenarios.

Table 4.3 Net present value of roof systems under various benefit scenarios over 40-years assuming conventional roof replacement at 20 years.

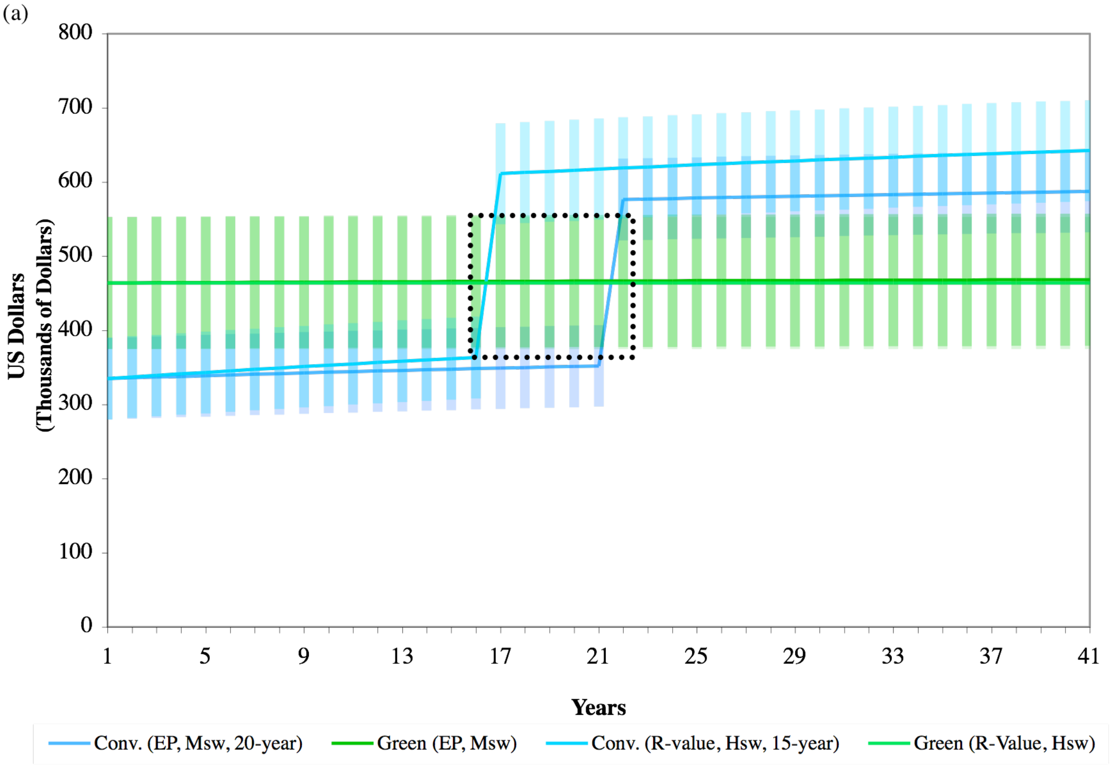
Net Present Value over 40 years	Roof Type		Percent change in NPV
	Conventional	Green	
R-Value; Mean Stormwater	$613,969	$468,366	23.72
EnergyPlus; Mean Stormwater	$587,465	$468,366	20.27
R-Value; High Stormwater	$619,828	$463,944	25.15
EnergyPlus; High Stormwater	$593,324	$463,944	21.81
Low Air Valuation; R-Value; Mean Stormwater	$613,969	$443,644	27.74
Low Air Valuation; EnergyPlus; Mean Stormwater	$587,465	$443,644	24.48
Low Air Valuation; R-Value; High Stormwater	$619,828	$439,222	29.14
Low Air Valuation; EnergyPlus; High Stormwater	$593,324	$439,222	25.97
High Air Valuation; R-Value; Mean Stormwater	$613,969	$374,611	38.99
High Air Valuation;EnergyPlus; Mean Stormwater	$587,645	$374,611	36.25
High Air Valuation; R-Value; High Stormwater	$619,828	$370,190	40.28
High Air Valuation; EnergyPlus; High Stormwater	$593,324	$370,190	37.61

Under novel methods (stormwater fees, energy savings, and air pollution uptake) over the 40-year lifetime of the roof, the NPV of the green roof system is between 25% (low air pollution benefit estimate with mean stormwater fee reduction and energy savings modeled from EnergyPlus) and 40% (high air pollution benefit estimate with high stormwater fee reduction and energy savings modeled from R-value analysis) less than the NPV for a conventional system (Figure 4.3, Table 4.3). The current valuation scenarios reveal that over 40 years, green roofs cost less than conventional roofs. Additionally, all valuation scenarios showed that the NPV of the conventional roof only exceeds the NPV of the green roof beginning when the cost of the roof replacement at the end of twenty years is included in the NPV.

To assess the dependency on roof longevity and to further assess the contribution of air pollution mitigation, the NPV of the conventional roof was assessed with replacement at 15 and 20 years (35). Figure 4.4 shows the net present value from year 0 to year t over the lifetime of the green roof system, considering the green roof valuation of (a) stormwater and energy savings and considering (b) all three environmental benefits. The incorporation of air pollution benefit reduces the green roof NPV by more than 5 percent under a low valuation estimate and by more than 20 percent for a high valuation estimate when evaluated against a conventional roof with a 20-year lifetime. Shifting the replacement up to year 15 increases the NPV of the conventional roof by 4 percent holding fees and energy costs constant.

Figure 4.4 Net present value (NPV) from 0 to year t over 40 years under (a) current methods of valuation (stormwater fees and energy savings), and (b) novel methods of valuations (stormwater fees, energy savings, and air pollution uptake). The range of NPV of the costs of the conventional roof is bounded according to (i) the mean NPV assuming a 15-year lifetime using the R-Value analysis method for energy expenditure and high stormwater fee, and (ii) the mean NPV assuming a 20-year lifetime using the EnergyPlus model and mean stormwater fees. The range for the NPV of total green roof costs is bounded according to (i) the mean NPV assuming the R-Value analysis method for energy and no fee, and (ii) the mean NPV assuming the EnergyPlus model for energy and 50% reduction in mean stormwater fee in both (a) and (b). The bars represent one standard deviation above and below the mean for each NPV scenario. The lower left side of the black box indicates where the lower bound of the green roof NPV is less than the mean NPV of the conventional roof. The upper right side of the black box indicates where the upper bound of the green roof NPV is less than the mean NPV of the conventional roof. The time required for this to occur for the mean costs is highly dependent upon the conventional roof replacement.

(a)


US Dollars
(Thousands of Dollars)
800
700
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300
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1
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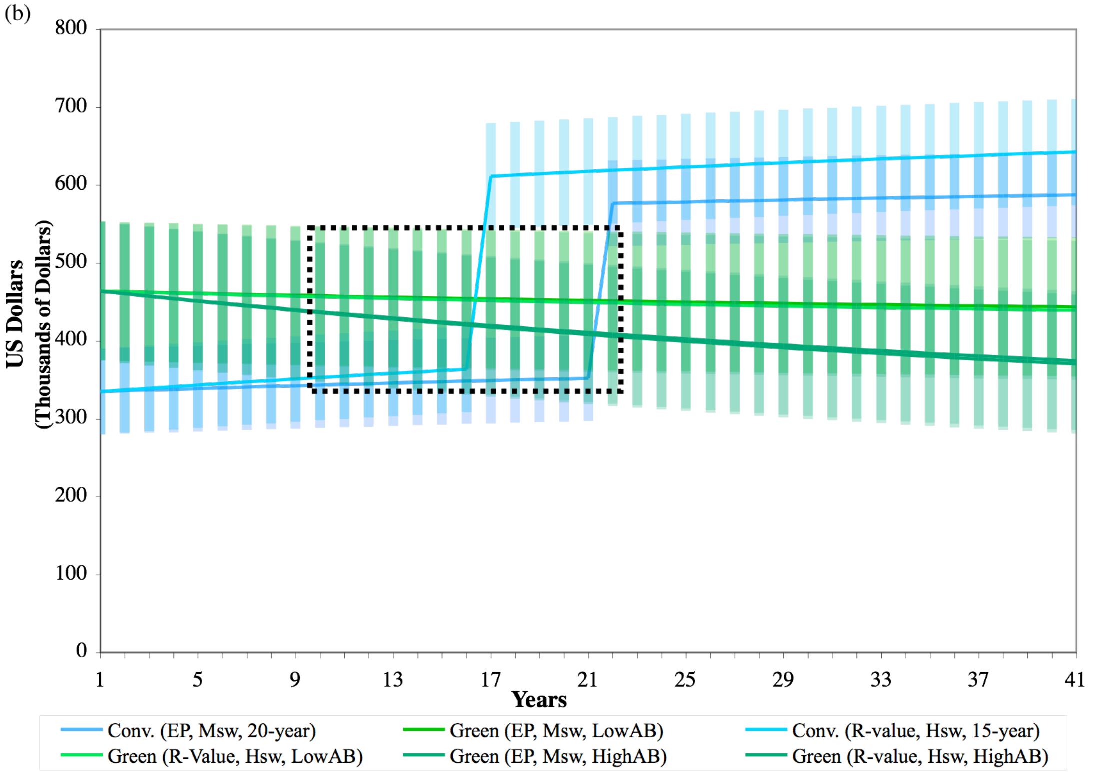
37
41
Years
Conv. (EP, Msw, 20-year)
Green (EP, Msw)
Conv. (R-value, Hsw, 15-year)
Green (R-Value, Hsw)

(b)


US Dollars
(Thousands of Dollars)
800
700
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37
41
Years
Conv. (EP, Msw, 20-year)
Green (EP, Msw, LowAB)
Conv. (R-value, Hsw, 15-year)
Green (R-Value, Hsw, LowAB)
Green (EP, Msw, HighAB)
Green (R-value, Hsw, HighAB)

While stormwater fees affect the NPV over 40 years, air pollution mitigation and energy savings have greater impact on the NPV as shown in the annual environmental benefits summary (Figure 4.5).

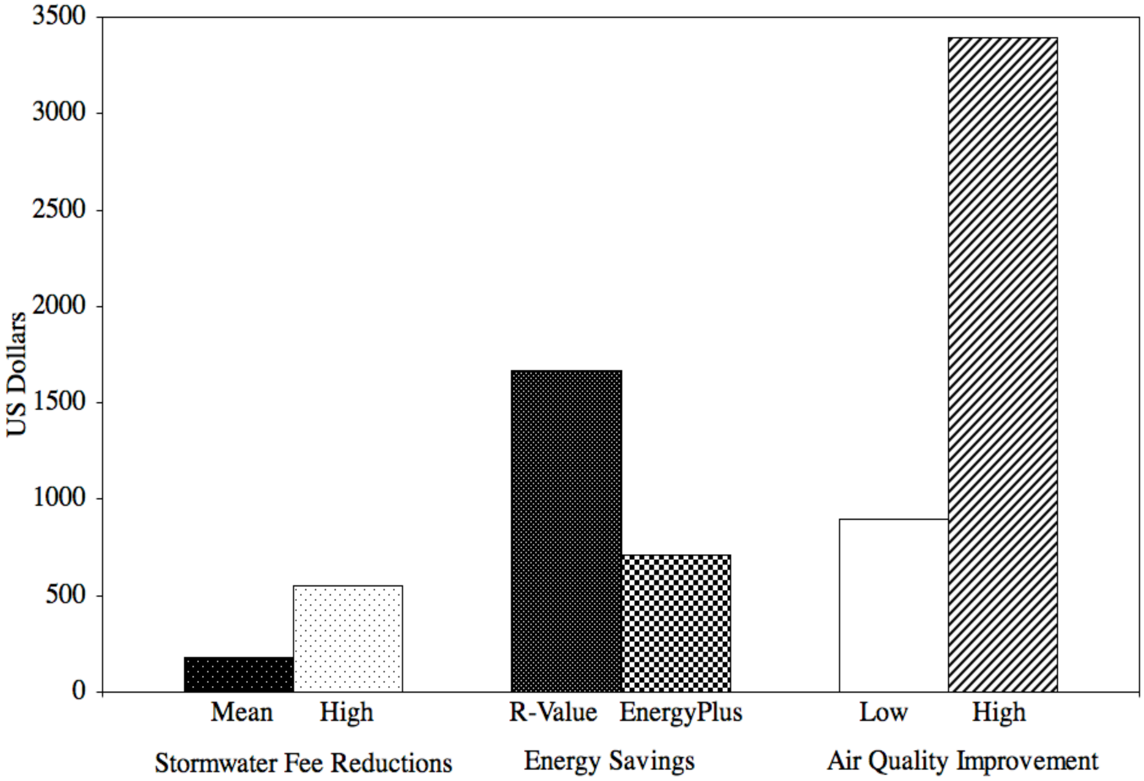


Figure 4.5 Annual environmental benefits for a 2000 m^2 green roof system in Ann Arbor, Michigan. These benefits were incorporated into the net present value analysis. Error bars were not displayed as uncertainty was not quantifiable for all benefits.

Additional savings due to reduced onsite stormwater infrastructure are not included at the building scale as infrastructure savings at individual building sites could only be realized for new building construction or significant renovation projects. Similarly, while system loads to HVAC were taken into account to determine the total reduction in energy, infrastructure savings (from size reduction) were not included. This analysis focused on the opportunity for green roofs on existing buildings that could support an extensive vegetated roof with minimal impact on the building and roof.

4.4. Policy Implications

The current method of valuation shows that the investment in green roof systems in the Mid-West may break even in 14-22 years, depending on the input variables and methods of benefits estimation (Figure 4.4). While roof replacement drives the outcome of the model in the absence of air pollution mitigation, the combination of energy and health benefits has the potential to impact the NPV prior to roof replacement. All other parameters remaining constant, more moderate climates would see less energy benefit from a green roof system while climates that require cooling or heating through much of a season may have a greater energy savings that reported here. Further, since the benefit attributable to NO_X uptake exceeds the modeled range of benefits from energy savings, the importance of including the social cost factor into the economic analysis is substantial. Further work is required to incorporate HVAC size reductions, stormwater infrastructure size reductions, and multiple air pollutant reductions. Results from this analysis show that the ability of green roofs to improve air quality should not be ignored by policymakers as its inclusion in a cost-benefit analysis influences the NPV.

Proper valuation of environmental benefits requires changes to current policies that affect green roofs. Two strategies that have potential to rectify the price discrepancy include (i) proper valuation of infrastructure costs via stormwater fees, and (ii) market-based tradable permit schemes for contribution to impaired local waterways similar to what currently being explored for nutrient runoff (Cheseapeake Bay Program, 2001). In addition to these policies, the air pollution mitigation ability of green roofs into an economic benefit would further reduce the NPV by 5 to 20 percent. This could be achieved through direct incentives (which would reduce the upfront cost of a green roof) or through the incorporation of green roofs as an abatement technology into existing regional air pollution emission allowance markets. Further research into these policy alternatives will aid the design and development of strategies to translate the societal and environmental benefits of green roofs to building owners that ultimately construct green roofs.

Chapter 5

Fugacity-based Multimedia Environmental Compartment Model

5.1. Introduction

It has been shown that green roofs have the potential to improve urban air quality through the reduction of particulate matter and uptake of air-borne pollutants (Banting et al., 2005; Deutsch et al., 2005). The previous chapter explored and demonstrated the opportunity for including the valuation of air quality improvement in a cost-benefit analysis. For appropriate valuation and integration of the technology in air emissions policies, the uptake potential must be rigorously quantified. Currently, the fate and transport mechanism of these pollutants on green roofs is not well understood. To quantitatively address this data gap, the boundary conditions describing uptake can be bounded by using physical-chemical characteristics of air pollutants as a proxy for fate analysis. Fugacity-based models allow for the incorporation of environmental compartments (e.g. air and soil), and for testing the impact of physical-chemical characteristics of a range of contaminant classes on their environmental behavior. Previous research on fugacity-based fate and transport models has focused on quantifying hydrophobic organic contaminant partitioning into vegetation (Mackay, 2001; NRC, 2004). Vegetation models have evaluated chemical partitioning at the greenhouse scale and regional scale for organic contaminants. Limited research has been conducted on the applicability of fugacity models to inorganic pollutants, in part due to the lack of availability of the required physicochemical parameters, and the different environmental behavior of these compounds relative to organic constituents. Fugacity-based models have explored the fate and transport of inorganic mercury and several interconverting species (both organic and inorganic) within the environment (Diamond, 1999; Diamond et al., 2000; Gandhi et al., 2007) . This chapter will detail the applicability of fugacity models to quantifying the fate of inorganic contaminants relevant to air pollution.

Nitrogen oxides (NO_X) represent a class of air pollutants regulated under the Clean Air Act (CAA). They are considered reactive, as they form ozone in the troposphere, in combination with volatile organic compounds (VOCs) and hydroxyl radicals, This reaction sequence increases human exposure to elevated ozone and NO_X concentrations in the air, thus impacting the risk of heart attacks and respiratory diseases (Brunekreef and Holgate, 2002; Bell et al., 2004). According to the American Lung Association, one-third of the US population in 2006 lived in areas with unhealthy levels of ozone (ALA, 2007). Many regulatory strategies exist including market-based cap and trade programs to help bring communities into attainment with the national ambient air quality standards. According to the CAA, for a region to receive pollutant allowances for a cap and trade program, the potential air quality improvement by an abatement technology must be rigorously quantified.

5.2. Methodology

To address this need, a custom fugacity model, “Sequestering Emissions: a Designable Uptake Model (SEDUM)”, was described to quantify the contaminant interactions in the air-vegetation-soil- compartments. The model is set up in a probabilistic mode to test the following variables: roof area, solid matrix properties, regional climate and atmospheric contaminant concentration data. This analysis was implemented using Monte-Carlo type simulations to quantify the uncertainty associated with the input parameters, and to propagate the uncertainty throughout the model to create an output probability space. By capturing the applicable boundary conditions for green roof air pollution mitigation, this information can aid policymakers in developing environmental and public health policies that mitigate risk in urban areas.

5.2.1. Species Selection of Reactive Nitrogen Compounds

To describe the environmental partitioning of nitrogen oxides within the green roof system, the significant reaction pathways in the troposphere and the uptake mechanisms within the soil and vegetation compartments needed to be incorporated. In polluted areas, nitrogen oxides (NOx), primarily in the form of nitric oxide (NO), are directly emitted to the atmosphere from incomplete fossil fuel combustion (e.g. vehicles, coal-fired power plants) (Jacob, 1999). Nitric oxide is generated from the oxidation of nitrogen and the thermal decomposition of air supplied to a combustion chamber (Jacob, 1999). Nitric oxide and nitrogen dioxide (NO_2) rapidly cycle in the atmosphere, and as a result, both NO and NO_2 are considered primary pollutants.

These primary pollutants form ozone in the troposphere via photochemical reactions with hydroxyl radicals and volatile organic compounds (VOCs) (Sillman, 2004). Additional reaction sequences lead to production of nitric acid (HNO_3), which can serve as a NO_X removal pathway (Sillman, 2004).

Daytime

$$NO_2 + OH + M \Rightarrow HNO_3 + M \qquad \text{(R 5.7)}$$

Nighttime

$NO_2 + O_3 \Rightarrow NO_3 + O_2$ (R 5.8)

$NO_3 + NO_2 + M \Rightarrow N_2O_5 + M$ (R 5.9)

$N_2O_5 + H_2O + \text{aerosol} \Rightarrow 2HNO_3$ (R 5.10)

Additional oxidized forms of NO_X are NO_3, N_2O_5, HONO, and HO_2NO_2; the acids (HONO, HO_2NO_2, and especially HNO_3) serve as the primary method for removal from the troposphere (Jacob, 1999).

Plants have been shown to assimilate nitrogen from NO_2 to organic compounds at concentrations above a compensation point (Kaji et al, 1980; Wellburn, 1990). A compensation point is the concentration in the atmosphere above which plants will take up NO_2 or other compound from the atmosphere; below that concentration plants may release the compound into the atmosphere. For NO_2, the compensation point is estimated at 2E-4 - 2.9E-3 μL/L; reported hourly concentrations of NO_2 in urban areas are above this point and range from 0.01-0.12 μl/L in the US and 0.02-0.19 μL/L in Japan to 0.25-0.4 μL/L in the UK (Johansson, 1987; Hanson and Lindberg, 1991). This model accounts for daylight steady-state concentrations of NO, NO_2, and HNO_3 as the reactive species that are primarily involved in transfer with soil and vegetation. This assumes that NO_3 is not significantly generated during daylight conditions.

There are additional species of reactive nitrogen compounds within the troposphere (including additional acids such as HONO and HO_2NO_2), yet less is known about their depositional pathways. While peroxyacetyl nitrate (PAN) is an important reservoir species of NO_X for long-term transport, this model is limited to local effects. As a result, these compounds and those compounds primarily associated with biogenic emissions (e.g. N_2O, NH_4) have been excluded from this analysis.

5.2.2. Mechanism of Uptake by Vegetation

There are generally two modes of transport of nitrogen compounds into the plant. Compounds may partition from soil to the plant roots to be transported via the xylem (Morikawa and Erkin, 2003), or they may deposit directly from the air via gas-phase and particle-phase dry and wet deposition (Hanson and Lindberg, 1991; Simonich and Hites, 1995; Sickles and Shadwick, 2007). For these compounds, exchange occurs on the cuticle of the leaf or via the stomata (Hanson and Lindberg, 1991). The cuticle is a waterproof layer comprised of cutin on the epidermal cells of the leaf. Cutin is a relatively inert compound that protects the leaf from degradation and water loss (Nobel, 2005). The stomata are pore spaces between two guard cells of the epidermis that allow CO_2 and other trace gases into the leaf for photosynthesis. Oxygen and water vapor are emitted through these pore spaces as well, and the spaces are adjustable to balance the influx of CO_2 required for photosynthesis with the inevitable water loss that occurs when the stomata are open (Nobel, 2005).

There is increasing evidence that plants take up NO_2 from the atmosphere. Hill (1971) proposed that vegetation may serve as a sink for atmospheric contaminants, and Rogers et al. (1979) observed assimilation of NO_2 by *Phaseolus vulgaris*. It has been assumed that primary nitrogen assimilation pathways convert NO_2 into organic nitrogenous compounds (Rogers et al., 1979; Yoneyama and Sasakawa, 1979; Kaji et al., 1980; Takahashi, 2001; Wellburn, 1990). Morikawa et al. (2004) indicated that NO_2 can also be converted to alternative nitrogen compounds allowing NO_2 to serve in a limited capacity as a nitrogen fertilizer. The extent of NO_2 uptake depends upon the atmospheric concentration (Rogers et al. 1979; Takahashi et al., 2005) and the plant species (Durmishidze and Nutsubidze, 1976; Morikawa et al., 1998; Takahashi et al., 2005).

Uptake of Nitrogen Dioxide (NO_2)

Leaf-level measurements are available for nitrogen dioxide (NO_2) from a variety of plant species. According to Hanson and Lindberg (1991), broadleaf and crop plants tend to have higher conductance (mean conductance between 1.2 and 1.3 mm s^{-1}) than conifer trees (mean conductance between 0.3 and 0.8 mm s^{-1}). The uptake rate generally increases proportionally to the atmospheric concentration of NO_2 with evidence of a 'compensation point' where below concentrations of 3nl l^{-1}, NO_2 does not deposit (Johansson, 1987). This compensation point may apply to rural areas but is below ambient concentrations in urban areas.

Several studies have shown that stomatal aperture controls NO_2 deposition (Saxe, 1986; Hanson et al., 1989; Okano et al., 1988). Hanson and Lindberg (1991) state that while cuticular deposition rates have been reported at 1-2 orders of magnitude less than stomata deposition, it should be included in calculations of NO_2 deposition.

Uptake of Nitric Oxide (NO)

The observed conductance of nitric oxide from trees and crops is less than reported values for NO_2. Stomatal conductance controls NO uptake although there is a passive diffusion pathway through the cuticle as well (Hill, 1971; Galbally, 1989). There is also a compensation point for nitric oxide although this too is not a concern in urban areas. Under denitrifying conditions, there is a potential for NO to volatilize from soil.

However, the secondary denitrifying emission tends to be nitrous oxide (N_2O) while NO is emitted in much smaller amounts (Galbally, 1989). Under saturated soil conditions, very little NO is emitted. Nitric oxide emissions are limited at low soil water content as well, but there is some emission when conditions are between drought and saturation (Galbally, 1989). The greatest potential for NO emission from soils occurs on soils where the biomass has burned (Galbally et al, 1987; Johansson and Granat, 1984). As the flux of nitric oxide to the atmosphere is significantly reduced under vegetated conditions (Galbally, 1989), and biomass burning is ignored due to the location of this system on top of a roof, SEDUM neglects the emission of NO from the soil media.

Uptake of Nitric Acid

HNO_3 is reported to have higher rates of deposition than other oxides of nitrogen. Vapor deposition varies from less than 5 to 27 nmol/m^2/s (Hanson and Garten, 1992). Deposition is dependent upon the plant type. Although conductance for hardwoods was lower (0.9- 3.4 mm/s) than for a loblolly pine (6-34 mm/s), 39-48 percent of the deposited HNO_3 remained bound in the hardwoods versus 3 percent in loblolly pine needles (Hanson and Garten, 1992). According to Marshall and Cadle (1989) and Cadle et al (1991), nitric acid deposition may occur via the cuticle and the stomata. Deposition of HNO_3 is highly sensitive to leaf boundary layer resistance and may predominate via deposition to the cuticle (Hanson and Garten, 1992).

When considering nitric acid deposition, nitrate deposition may also occur. However, Meyers et al. (1991) found that nearly all deposited nitrogen (HNO_3+NO_3^-) was in the form of HNO_3. Dry deposition was estimated to provide between 30-50% of total input from atmosphere for observed sites in the eastern US (Meyers et al, 1991).

Both dry and wet deposition play a role in the reactive nitrogen species exchange between air-plant-soil surfaces.

Factors Affecting Uptake by Vegetation

Several factors affect uptake of reactive nitrogen species by vegetation, and are directly related to their water solubility, vapor pressure, and octanol-water partitioning coefficient. Factors that affect lipophilic organic pollutant accumulation from air to plant include vapor-particle partitioning in the atmosphere, octanol-air partition coefficient, and the plant species (according to Simonich and Hites, 1995). Gas-phase pollutants with a large K_{OA} are preferentially accumulated in plants (Simonich and Hites, 1995).

Both environmental conditions and plant-specific characteristics affect uptake as well (Susarla et al., 2002). Lipophilic compounds (those with K_{OW} greater than 10^4) partition to the epidermis of the root or to the soil particles and tend to not be drawn into the inner root xylem of the plant (Simonich and Hites, 1995). As a result, those compounds are often not translocated into the plant and not significantly metabolized (Simonich and Hites, 1995; Trapp et al., 1990). Hydrophilic compounds are taken up from the soil through the root system for compounds with high water solubilities, low Henry’s constants, and low K_{OW} values (Simonich and Hites, 1995) (Morikawa and Erkin, 2003). These compounds can be taken up by the plant and metabolized (Simonich and Hites, 1995). Table 5.1 lists the relevant physical chemical parameters for the selected reactive nitrogen species. For those parameters where data were not available, KOWWIN, a program that is part of the US EPA’s EPISuite, was used (EPA, 2007b). This estimation method is based on an atom-fragment method to predict inorganic, ionized species (Meylan and Howard, 1995).

Table 5.1 Physical chemical parameters of selected reactive nitrogen species used in SEDUM.

Chemical Formula	**HNO_3**	**NO**	**NO_2**
Molecular Mass (g/mole)	63	30	46
Data Temperature (Celsius)	25	25	25
Henry's law constant (Pa m^3/mol)*	4.83E-04	5.33E+04	1.01E+05
K_{OW} †	1.62	1.26	0.26
K_{AW}*	1.95E-07	2.15E+01	4.09E+01
K_{OA}*†	8.32E+06	5.85E-02	6.36E-03

*Seinfeld and Pandis, 1998. † EPA, 2007b.

5.2.3. Sequestering Emissions: Designable Uptake Model (SEDUM)

The developed fugacity-based model, SEDUM (Sequestering Emissions: Designable Uptake Model) describes the green roof system through three compartments, air, soil, and vegetation (Figure 5.1). SEDUM is based upon a Level III (Version 2.80) fugacity model (Canadian Environmental Modelling Centre, CEMC), which assumes steady-state, but not equilibrium, between environmental compartments. The CEMC model is a six-compartment environmental model that includes air, soil, water, sediment, suspended sediment, and aquatic biota (Mackay, 2001). For the purposes of green roof system modeling, only the air and soil compartment are included. Additionally, a vegetation compartment was added and changes to the soil compartment were made to account for the green roof. These changes to the soil compartment include a shallow depth due to weight restrictions on the roof and an additional water runoff removal pathway to account for stormwater percolating through the soil media and exiting the roof via conventional stormwater drains. While water and aerosols are used to model atmospheric deposition to the vegetation and soil compartments, they are assumed to have a volume of zero for compartment modeling in SEDUM (Hung and Mackay, 1997; Cousins and Mackay, 2001; Severinsen and Jager, 1998). Due to this assumption, SEDUM provides contaminant concentration information only on stormwater runoff instead of for the larger free surface water compartment. A summary of the modeled transport methods is in Figure 5.1; the methodology is discussed in greater detail in Chapter 3.

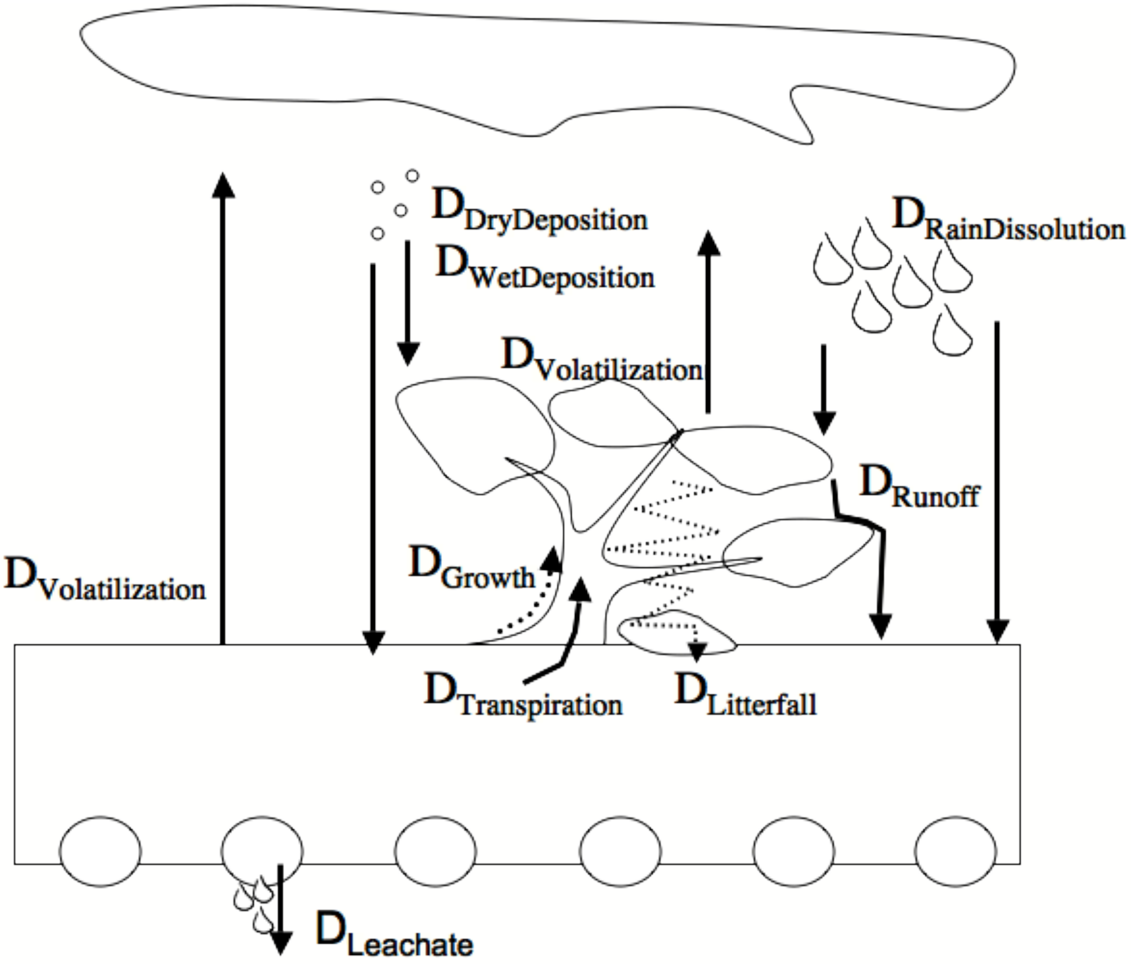


Figure 5.1 Principal intermedia transfer terms within the air-soil-vegetation compartment system as modeled in SEDUM.

5.2.4. Mass Balance Equations

Transport processes within compartments and between each compartment were developed from the CEMC Level III model, previous vegetation models, and soil-air exchange models (Hung and Mackay, 1997; Cahill et al, 2003; Cousins and Mackay, 2001; Mackay, 2001). Table 5.2 summarizes these equations. The transport parameters were used in the mass balance equations for each compartment.

Table 5.2 Intermedia Transfer (D) Values used in SEDUM.

Process	**D value**	**Definition (mol Pa^{-1} h^{-1})**
Advection in air	D_{AdvAir}	$G_{Air} \cdot Z_{Air}$
Reaction in air	D_{RxnAir}	$V_{Air} \cdot Z_{Air} \cdot k_{Air}$
Reaction in soil	$D_{RxnSoil}$	$V_{Soil} \cdot Z_{Soil} \cdot k_{Soil}$
Reaction in vegetation	$D_{RxnVegetation}$	$V_{Vegetation} \cdot Z_{Vegetation} \cdot k_{Vegetation}$
Intermedia Transfer	**D value**	**Definition (mol Pa^{-1} h^{-1})**
Air to Soil	$D_{AirSoil}$	$D_E + D_{RWS} + D_{QWS} + D_{QDS}$
Soil to Air	$D_{SoilAir}$	D_E
Effective diffusion	D_E	$(1 / (k_{EA} \cdot A_S \cdot Z_{Air}) + Y_S / (A_S(B_{EA} \cdot Z_{Air} + B_{EW} \cdot Z_{Water})))^{-1}$
Rain wet dissolution	D_{RWS}	$A_S \cdot U_R \cdot Z_{Water}$
Wet particle deposition	D_{QDS}	$A_S \cdot U_R \cdot Q \cdot v_Q \cdot Z_{Aerosol}$
Dry particle deposition	D_{QWS}	$A_S \cdot U_Q \cdot Q \cdot v_Q \cdot Z_{Aerosol}$
Air to Vegetation	$D_{AirVegetation}$	$D_{GDV} + D_{RWV} + D_{DPV} + D_{WPV}$
Vegetation to Air	$D_{VegetationAir}$	D_{GDV}
Gaseous deposition	D_{GDV}	$(1 / (A_S \cdot L \cdot U_C . Z_{Vegetation}) + 1 / (A_S \cdot L \cdot U_B \cdot Z_{Vegetation}))^{-1}$
Rain wet dissolution	D_{RWV}	$FrUF \cdot A_S \cdot U_R \cdot Z_{Water}$
Wet particle deposition	D_{DPV}	$FrUF \cdot A_S \cdot U_R \cdot Q \cdot v_Q \cdot Z_{Aerosol}$
Dry particle deposition	D_{WPV}	$A_S \cdot U_D \cdot Q \cdot v_Q \cdot Z_{Aerosol}$
Vegetation to Soil	$D_{VegetationSoil}$	$D_{Runoff} + D_{Litterfall} - D_{Growth}$
Runoff	D_{Runoff}	$(1 - FrUF) \cdot (D_{RWV} + D_{WPV})$
Litterfall	$D_{Litterfall}$	$(1 / t_V) \cdot v_V \cdot Z_{Vegetation}$
Growth	D_{Growth}	$D_{Litterfall}$
Soil to Vegetation	$D_{SoilVegetation}$	$Tr \cdot A_S \cdot L \cdot TSCF \cdot Z_{Water}$

As SEDUM accounts for multiple reactive nitrogen species, concentration ratios of the three species were incorporated into the model to determine partitioning of all three compounds as related to one another (Toose and Mackay, 2004). Since HNO_3 is the principal deposition pathway (Meyers et al, 1991), it was selected as the key species for the model. The concentrations of the other two compounds (NO and NO_2) were calculated based on the fugacities of HNO_3 and their relative ratios in each environmental compartment (Table 5.3).

Table 5.3 Concentrations and half-lives of selected reactive nitrogen species in the three environmental compartments.

Parameter	Species	Value	Unit	Source
Vegetation				
Concentration	HNO_3	0.46-0.81	$molNO_3/m^3$	Takahashi et al, 2005
	NO_2	0.20-2.71	$molNO_2/m^3$	Takahashi et al, 2005
	NO	0.09-1.27	$molNO/m^2$	Takahashi et al, 2005; Hanson and Lindberg, 1991
Half-life	HNO_3	4	hours	Morikawa et al, 2004
	NO_2	2.5	hours	Morikawa et al, 2004
	NO	8.3^*	hours	Singh, 1987
Soil				
Concentration	HNO_3	3.81E-01	$molNO_3/m^3$	Galbally et al, 1985
	NO_2	2.76E-02	$molNO_2/m^3$	Galbally et al, 1985
	NO	0.00E+00	$molNO/m^3$	
Half-life	HNO_3	5	hours	Baumgärtner and Conrad, 1992
	NO_2	4	hours	Baumgärtner and Conrad, 1992
	NO	0	hours	Baumgärtner and Conrad, 1992
Air				
Concentration	$HNO_3^{\dagger}$	8.18E-10 - 1.23E-8	mol/m^3	Seinfeld, 1986
	HNO_3^{Δ}	1.23E-7 - 2.05E-6	mol/m^3	Seinfeld, 1986
	$NO_2^{\dagger}$	4.09E-10 - 2.05E-8	mol/m^3	Seinfeld, 1986
	NO_2^{Δ}	2.05E-6 - 1.02E-5	mol/m^3	Seinfeld, 1986
	$NO^{\dagger}$	4.09E-10 - 2.05E-9	mol/m^3	Seinfeld, 1986
	NO^{Δ}	2.05E-6 - 3.07E-5	mol/m^3	Seinfeld, 1986
Half-life	HNO_3	183	hours	Singh, 1987
	NO_2	8.3	hours	Singh, 1987
	NO	8.3	hours	Singh, 1987

* In absence of vegetation half-life, the air half-life is used. † Unpolluted. Δ Polluted.

Several assumptions were made for this table. As reference values for concentration and half-life for nitric oxide could not be found and the flux of nitric oxide to the atmosphere is significantly reduced under vegetated conditions (Galbally, 1989), an initial concentration was assumed to be 0. As there is the potential for NO to volatilize from soil under denitrifying conditions (in amounts significantly less than nitrous oxide emissions), a half-life of 0 was used under the assumption that any nitric oxide generated in the soil compartment would be immediately released to the atmosphere. A half-life for nitric oxide could also not be found for the vegetation compartment. A conservative value of 8.3 hours was assumed for this compartment (the same as the air compartment) assuming that if no reactions converted NO to a usable form for metabolic uptake that NO would oxidize to NO_2 and follow reaction sequence 5.8 through 5.10 at night. Regarding initial concentrations in air, the mean polluted ranges were used for determining fugacity ratios. The presented values for unpolluted areas could apply in non-urban areas.

The fugacity ratios are based upon the intermedia transfer (D) values for each species and are integrated into the rate equations as shown below (Toose and Mackay, 2004).

$$Q = f_1D_1 + f_2D_2 + f_3D_3 = f_1D_1\left(1 + \frac{f_2D_2}{f_1D_1} + \frac{f_3D_3}{f_1D_1}\right) \tag{5.61}$$

Substituting R_i for $f_iD_i/(f_1D_1)$ simplifies the total rate equation

$$Q = f_1D_1\left(1 + \frac{f_2D_2}{f_1D_1} + \frac{f_3D_3}{f_1D_1}\right) = f_1D_1\left(1 + R_2 + R_3\right) \tag{5.62}$$

The key species rate equation is then multiplied by the sum of the relative ratios of each species, R_T, which is incorporated into the compartment mass balance equations to determine the fugacity in each compartment.

Air Compartment

$$E_A + G_A C_A + f_S D_{SA} R_{TSA} + f_V D_{VA} R_{TVA} = f_A \left(D_{AS} R_{TAS} + D_{AV} R_{TAV} + D_{rxnA} R_{TrxnA} + D_{advA} R_{TadvA} \right)$$

Soil Compartment

$$f_A D_{AS} R_{TAS} + f_V D_{VS} R_{TVS} = f_S \left(D_{SA} R_{TSA} + D_{SV} R_{TSV} + D_L R_{TL} + D_{rxnS} R_{TrxnS} \right)$$

Vegetation Compartment

$$f_A D_{AV} R_{TAV} + f_S D_{SV} R_{TSV} = f_V \left(D_{VA} R_{TVA} + D_{VS} R_{TVS} + D_{rV} R_{TrV} \right)$$

A depiction of the air-soil-vegetation environmental system that SEDUM describes is shown in Figure 5.1. SEDUM was developed in Microsoft Excel; the spreadsheet program allowed for integration with existing probabilistic modeling software.

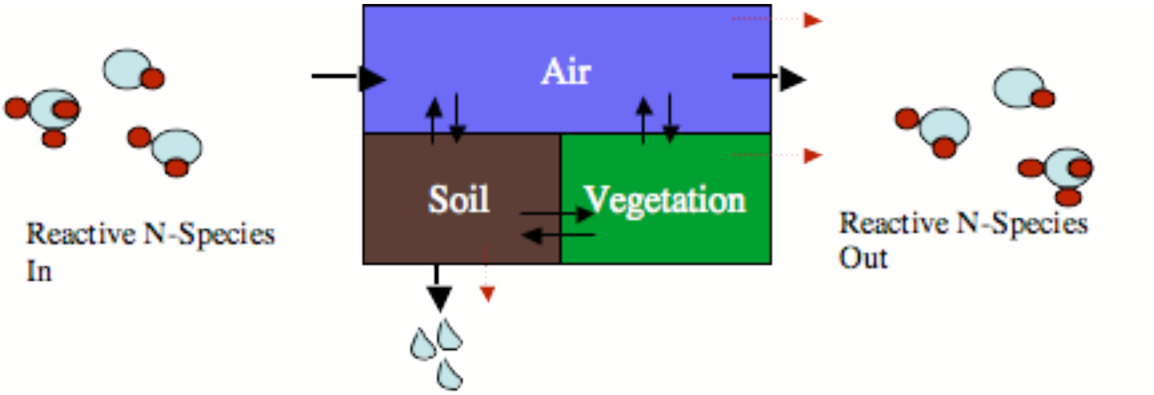


Figure 5.2 SEDUM configuration. The model includes the air, soil, and vegetation compartments and provides information on runoff. The selected reactive nitrogen species are depicted. Black arrows show the major transport mechanisms into and out of SEDUM and between compartments. The red arrows show the reactive loss pathways within each compartment.

A probabilistic based sensitivity analysis was performed using Crystal Ball 7.3 (Oracle, 2007). Crystal Ball integrates into Microsoft Excel to enable Monte Carlo simulations, a probabilistic method that uses pseudo-random numbers within a stated range for input parameters. Ranges and distributions were provided for model inputs according to Hertwich et al. (1999).

Table 5.4 Ranges and distributions for environmental inputs (Hertwich et al, 1999).

Environmental Parameters	Mean	CV	Distribution
Land Area (m2), A_{AS}	5.42E+08†	0.1	Normal
Wind Speed (m/h)	16100†	1	Triangular
Rain rate (m3rain/m2area/h), U_R	1.00E-04†	1	Triangular
Soil depth (m)	0.102	1	Triangular
Organic carbon content	0.1	1	Triangular
Soil density (kg/m3)	1500-2600	‘—	Uniform
Volume fraction of soil that is air, v_A	0.17	0.2	Normal
Volume fraction of soil that is water, v_W	0.28	0.2	Normal
Foliage density (kg/m3)	1000	0.2	Normal

† Mean values based on Detroit metropolitan area.

For parameters where experimental data were obtained (initial concentration values), ranges were used instead of the coefficient of variation (see Table 5.3) (Galbally et al, 1985; Seinfeld, 1986; Singh, 1987; Morikawa et al., 2004; Takahashi et al, 2005; Hanson and Lindberg, 1991; Baumgärtner and Conrad, 1992).

5.3. Results and Discussion

SEDUM was run 10,000 times to obtain a standard error for the distribution of runs that was two orders of magnitude less than the standard deviation of any mean input or output parameter. The standard error of the mean is related to the standard deviation of a population and the number of trials through the following equation:

$$S.E. = \frac{\sigma}{\sqrt{N}} \tag{5.63}$$

Initially, SEDUM was run with 30 input parameters and their associated uncertainty. These include physical and chemical characteristics, as well as environmental parameters specific to a location and the design of a green roof system. The results from this initial analysis are shown in Table 5.5. The reported fugacities are shown for the key species (HNO_3) only, but concentrations are reported for all three species. The fugacity is greatest in air (mean of 2.49E-9 Pa) compared to the other compartments (mean of 1.42E-10 Pa for soil, 2.03E-11 Pa for vegetation), suggesting that HNO_3 will readily transfer from the air compartment to soil and vegetation. The fugacity is lowest in the vegetation compartment suggesting that HNO_3 is less likely to escape that compartment.

Table 5.5 SEDUM results for compartment fugacities and species concentrations.

Statistics (n=10000)		**Mean**	**Median**	**Standard Deviation**	**Mean Standard Error**
Fugacity	Air Pa	2.49E-9	2.22E-9	1.52E-9	1.52E-11
	Soil Pa	1.42E-10	1.03E-10	1.29E-10	1.29E-12
	Vegetation Pa	2.03E-11	1.61E-11	1.60E-11	1.60E-13
Concentration in Air	HNO_3 mol/m^3	1.01E-12	8.94E-13	6.13E-13	6.13E-15
	NO mol/m^3	1.28E-11	1.29E-11	3.16E-12	3.16E-14
	NO_2 mol/m^3	4.75E-12	4.38E-12	2.38E-12	2.38E-14
Concentration in Soil	HNO_3 mol/m^3	3.53E-8	2.84E-8	2.68E-8	2.68E-10
	NO mol/m^3	5.79E-10	3.27E-10	1.33E-9	1.33E-11
	NO_2 mol/m^3	3.42E-8	1.65E-8	9.16E-8	9.16E-10
Concentration in Vegetation	HNO_3 mol/m^3	6.80E-10	5.39E-10	5.33E-10	5.33E-12
	NO mol/m^3	7.43E-10	5.49E-10	6.75E-10	6.75E-12
	NO_2 mol/m^3	1.59E-9	1.18E-9	1.48E-9	1.48E-11

For all three compounds, the highest concentrations appeared in the soil compartment with the most dilute concentration in air. The mean nitric acid and nitrogen dioxide concentrations in the soil compartment were similar (3.53E-8 mol/m^3 and 3.42E-8 mol/m^3 respectively) and two orders of magnitude greater than nitric oxide (5.79E-10 mol/m^3). In the vegetation compartment, the nitrogen dioxide concentration (1.59E-9 mol/m^3) was more than two times greater than either the nitric acid (6.8E-10 mol/m^3) or nitric oxide (7.43E-10 mol/m^3) concentrations.

Table 5.6 SEDUM results for mass of species in compartments.

Statistics (n=10000)		**Mean**	**Median**	**Standard Deviation**	**Mean Standard Error**
Mass in Air	HNO_3 kg	2.04E-1	1.82E-1	1.22E-1	1.22E-3
	NO kg	1.24E+0	1.26E+0	2.73E-1	2.73E-3
	NO_2 kg	7.03E-1	6.54E-1	3.42E-1	3.42E-3
Mass in Soil	HNO_3 kg	1.33E-1	1.13E-1	8.44E-2	8.44E-4
	NO kg	1.04E-3	6.32E-4	2.29E-3	2.29E-5
	NO_2 kg	9.43E-2	4.86E-2	2.47E-1	2.47E-3
Mass in Vegetation	HNO_3 kg	1.72E-2	1.39E-2	1.33E-2	1.33E-4
	NO kg	8.97E-3	6.66E-3	8.07E-3	8.07E-5
	NO_2 kg	2.95E-2	2.20E-2	2.72E-2	2.72E-4

Table 5.6 shows the mass distribution of the same trials at steady-state from the three environmental compartments. These values account for the total volume of each compartment. Although the soil compartment had the highest concentration of HNO_3 and NO_2 and the vegetation compartment had the highest concentration for NO, the air compartment contains the majority of all three species. The soil compartment contains the second greatest amount of HNO_3 and NO_2 while the vegetation compartment contains the second greatest amount for NO. Within the soil compartment, the species with the greatest mass is HNO_3. Within the vegetation compartment, the greatest is NO_2, which agrees with experimental observations of NO_2 uptake by vegetation (Hanson and Garten, 1992). For this run, assuming a release of 225 moles of NO_2 per hour, at steady-state the

green roof (soil media and vegetation) would contain 4.59E-10 ± 4.74E-10 kgNO_2/m^2. Annual removal rate will be discussed later in this chapter.

5.3.1. Sensitivity Analysis

Both Table 5.5 and Table 5.6 show that within the vegetation and soil compartments, the standard deviations were larger than the reported means when varying all thirty parameters. This suggests that further refinement of the uncertainty of parameters is needed. The 30 parameters include physical and chemical parameters as well as environmental parameters specific to a location and the design of a green roof system. Seventeen parameters affected the predicted species concentrations within the compartments by more than ten percent. This predictive uncertainty was considered sufficient to: (i) collect further site-specific information to constrain the model (environmental parameters), or to (ii) inform the design of a green roof (design parameters). These seventeen are listed in Table 5.7 under scenario specific parameters and chemical and environmental parameters.

Table 5.7 Initial screening of parameters listing those variables that alter species concentrations by more than 10%.

Sensitive Parameters
Design Parameters
Land area
Soil organic carbon content
Soil depth
Soil density
Soil Initial HNO_3
Environmental Parameters
Soil Initial NO
Soil Initial NO_2
Vegetation Initial HNO_3
Vegetation Initial NO
Vegetation Initial NO_2
Air Initial HNO_3
Air initial NO
Air initial NO_2
Half-life of NO in air
Half-life of HNO_3 in soil
Half-life of HNO_3 in vegetation
K_{OW} of HNO_3

Recognizing that input parameters contain both design parameters and location specific climate parameters (air pollution concentration), which could be measured for specific scenarios, a sensitivity analysis was conducted on the remaining environmental input parameters that influenced the output fugacities, concentrations, and relevant loss pathways by more than 10% (see Table 5.8). Relevant loss pathways are used to determine annual removal rates of reactive nitrogen species and include reactive losses in soil (D_{rS}), reactive losses in vegetation (D_{rV}), and advective losses due to stormwater leaching from the green roof system (D_L).

Table 5.8 Sensitivity analysis listing environmental parameters that alter fugacities, concentrations, and relevant losses by more than 10%. Excludes design and climate parameters.

Input	Range of Variation		Sensitive Output Parameter	Range of Variation		Mean	% Range of Mean
	Downside	Upside		Downside	Upside		
1/2-life in soil HNO_3	3.6E+09	2.1E+09	DrS HNO_3	3.72	6.28	2.8E+09	51.26
	2.8E-10	4.5E-10	NO in Soil	3.72	6.28	3.6E-10	47.89
	2.3E-08	3.8E-08	HNO_3 in Soil	3.72	6.28	3.0E-08	47.89
	7.9E-11	1.3E-10	Fugacity in Soil	3.72	6.28	1.0E-10	47.89
	1.4E-08	2.3E-08	NO_2 in Soil	3.72	6.28	1.9E-08	47.89
	5.1E-10	6.1E-10	HNO_3 in Vegetation	3.72	6.28	5.6E-10	18.09
	5.5E-10	6.6E-10	NO in Vegetation	3.72	6.28	6.0E-10	18.09
	1.2E-09	1.4E-09	NO_2 in Vegetation	3.72	6.28	1.3E-09	18.09
	1.5E-11	1.8E-11	Fugacity in Vegetation	3.72	6.28	1.7E-11	18.09
1/2-life in vegeta-tion HNO_3	3.5E+09	1.8E+09	DrS HNO_3	2.72	5.28	2.6E+09	64.08
	4.1E-10	7.9E-10	NO in Vegetation	2.72	5.28	6.0E-10	63.85
	3.8E-10	7.4E-10	HNO_3 in Vegetation	2.72	5.28	5.6E-10	63.85
	1.1E-11	2.2E-11	Fugacity in Vegetation	2.72	5.28	1.7E-11	63.85
	8.8E-10	1.7E-09	NO_2 in Vegetation	2.72	5.28	1.3E-09	63.85
K_{OW} HNO_3	1.8E-11	1.6E-11	Fugacity in Vegetation	1.53	1.71	1.7E-11	14.24
	2.2E+09	2.5E+09	DrV HNO_3	1.53	1.71	2.4E+09	11.05
	1.1E-10	9.9E-11	Fugacity in Soil	1.53	1.71	1.0E-10	10.37
Vegeta-tion initial HNO_3	1.5E-09	1.1E-09	NO_2 in Vegetation	0.54	0.73	1.3E-09	30.52
	7.1E-10	5.2E-10	NO in Vegetation	0.54	0.73	6.2E-10	30.52
Vegeta-tion initial NO	3.1E-10	8.9E-10	NO in Vegetation	0.35	1.01	6.0E-10	95.92
Vegeta-tion initial NO_2	6.7E-10	1.9E-09	NO_2 in Vegetation	0.76	2.15	1.3E-09	95.36

The half-life of nitric acid in vegetation and soil affect both fugacities and the concentrations of all species in both compartments. The uncertainty in the initial concentrations of all three species in the vegetation compartment affect the ultimate concentrations of nitric oxide and nitrogen dioxide within the plant compartment due to the constant species ratio assumption used in the model.

5.3.2. Scenario Testing

SEDUM was then used for reanalysis of the parameters as applied to two large-scale greening scenarios, including Washington, DC (Scenario 1) and in Toronto, Ontario (Scenario 2). Climate parameters and emissions data were obtained for both projects and are summarized in Table 5.9.

Table 5.9 Summary of scenario parameters for Washington, DC and Toronto, Ontario.

Parameters	**Washington, DC**	**Source**	**Toronto, Ontario**	**Source**
Total land area (m^2)	1.59E+08	USGS	6.32E+08	Banting et al, 2005
Green roof area	1.86E+06	Deutsch et al, 2005	4.98E+07	Banting et al, 2005
Annual NO_X emissions ($kgNO_2/y$)	1.48E+04	US EPA	4.62E+04	EC NPRI
Ambient NO_X concentration (mol/m^3)	9.82E-08	US EPA	9.03E-08	EC NPRI
Annual rainfall (mm)	1062	NCDC	818	Banting et al, 2005

Running SEDUM for Scenarios 1 and 2 reduced the uncertainty for the model relative to the base case. Table 5.10 and Table 5.11 show the fugacity, concentration, and mass results for this scenario. These support the trends observed in the base case with respect to concentration and mass distribution, as well as fugacity.

Table 5.10 SEDUM results for Scenario 1 once designable, measurable, and known parameters are defined.

Statistics (n=10000)		Mean	Median	Standard Deviation	Mean Standard Error
Fugacity	Air Pa	8.97E-5	8.97E-5	2.33E-12	2.33E-14
	Soil Pa	6.76E-6	5.54E-6	4.30E-6	4.30E-8
	Vegetation Pa	1.52E-6	8.18E-7	4.50E-6	4.50E-8
Concentration in Air	HNO_3 mol/m^3	3.62E-8	3.62E-8	9.40E-16	9.40E-18
	NO mol/m^3	1.81E-7	1.81E-7	4.70E-15	4.70E-17
	NO_2 mol/m^3	1.81E-7	1.81E-7	4.70E-15	4.70E-17
Concentration in Soil	HNO_3 mol/m^3	1.50E-3	1.50E-3	2.90E-4	2.90E-6
	NO mol/m^3	1.90E-5	1.84E-5	8.61E-6	8.61E-8
	NO_2 mol/m^3	1.09E-3	9.44E-4	7.66E-4	7.66E-6
Concentration in Vegetation	HNO_3 mol/m^3	3.00E-5	2.84E-5	1.13E-5	1.13E-7
	NO mol/m^3	3.26E-5	2.96E-5	1.80E-5	1.80E-7
	NO_2 mol/m^3	6.95E-5	6.34E-5	3.78E-5	3.78E-7

Table 5.11 SEDUM results for amount of species in each compartment for Scenario 1 once designable, measurable, and known parameters are defined.

Statistics (n=10000)		Mean	Median	Standard Deviation	Mean Standard Error
Mass in Air	HNO_3 kg	25.42	25.42	6.60E-7	6.60E-9
	NO kg	60.53	60.53	1.57E-6	1.57E-8
	NO_2 kg	92.82	92.82	2.41E-6	2.41E-8
Mass in Soil	HNO_3 kg	17.52	17.52	3.40	3.40E-2
	NO kg	0.11	0.10	4.80E-2	4.80E-4
	NO_2 kg	9.34	8.07	6.55	6.55E-2
Mass in Vegetation	HNO_3 kg	2.63	2.50	0.99	9.89E-3
	NO kg	1.36	1.24	0.75	7.54E-3
	NO_2 kg	4.45	4.06	2.43	2.43E-2

The SEDUM model predictions can be compared to data derived from analysis using the Urban Forest Effects (UFORE) D model of the Washington, DC area (Deutsch et al, 2005). Since SEDUM calculates total annual removal via reactive losses or transport from the green roof system, the removal rates can be separated by vegetation, soil, and stormwater runoff leaving the roof system. By limiting removal to the vegetation compartment, the SEDUM predictions can be compared to UFORE. The UFORE D model quantifies a number of parameters from local measurements including the urban forest composition, hourly biogenic volatile organic compound (BVOCs) emissions, hourly pollution removal by the forest and percent improvement in air quality (Nowak et al., 2005). The model is dependent upon plant species and assumes a 50:50 mix of grasses and evergreen shrubs for green roofs.

Table 5.12 details results from the two models for Washington, DC and a similar scenario for Toronto as compared to available UFORE D results (Banting et al, 2005). The predicted mean annual uptake by SEDUM is 2.1 to 2.7 times greater than UFORE-D model for these scenarios.

Table 5.12 Annual removal of reactive nitrogen species from air due to green roofs as determined by SEDUM and the UFORE Model.

Method	City Scenario Annual Uptake (kgNO2/m2/y)				Ratio (SEDUM/UFORE)	
	Toronto, ON		Washington, DC		Toronto, ON	Washington, DC
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Mean
UFORE	1.50E-03	--	1.10E-03	--	--	--
SEDUM* (vegetation)	3.16E-03	8.11E-03	2.94E-03	1.10E-02	2.11	2.67
SEDUM* (green roof)	1.43E-02	8.82E-03	1.42E-02	1.15E-02	9.50	12.88

* Total annual uptake using SEDUM includes three selected reactive nitrogen species as metabolized by the vegetation and soil compartments and as removed by the stormwater runoff from the green roof system. The term *vegetation* refers to the contribution of uptake only attributable to the vegetation compartment while *green roof* refers to the removal by the complete green roof system.

The differences can be explained as follows. First, the UFORE-D model considers dry deposition onto vegetation as the primary transport process from air to vegetation (Nowak et al., 2005). Model results are determined from calculations of atmospheric pollutant flux, boundary resistance, and a hybrid of a big-leaf and multilayer canopy model assuming a mix of grasses and shrubs for the green roof system (Nowak et al., 2005). As periods of precipitation were assumed to result in no pollutant uptake, the reported values of NO_2 uptake using the UFORE-D model would be expected to be less than the values provided by SEDUM for multiple species (Hanson and Lindberg, 1991; Bytnerowicz and Fenn, 1996) and includes both wet and dry deposition (Brimblecombe and Dawson, 1984; Anatolaki and Tsitouridou, 2007; Sickles and Shadwick, 2007). According to Sickles and Shadwick (2007), HNO_3 deposition dominates dry deposition of nitrogen species in the eastern United States (over 90% of oxidized nitrogen dry deposition and over 75% of total nitrogen dry deposition). Of the depositional pathways, wet deposition is a significant contributor to total deposition with dry deposition only contributing to 38% of total oxidized nitrogen deposition (Sickles and Shadwick, 2007). However, where precipitation is not as frequent, according to Anatolaki and Tsitouridou (2007), dry deposition dominates (75% of total deposition).

Second, the SEDUM prediction incorporates multiple reactive nitrogen species, whereas UFORE calculations were limited to NO_2. Both accounting for multiple species and precipitation may explain why SEDUM predicts uptake values much higher than UFORE D. SEDUM can also estimate uptake by the entire green roof system. When this is done as shown in Table 5.12, the uptake is 9.5 to 12.88 times higher than that predicted by the UFORE-D model. As observed by Hanson and Garten (1992), not all HNO_3 deposition onto plants remains on plants. It is therefore likely that throughfall during rain events would contain additional HNO_3 and may explain the additional uptake in soil and stormwater runoff.

The transport loss of anthropogenic nitrogen species from the green roof occurs through stormwater runoff. Table 5.13 compares water quality data from a green roof at York University in Toronto, Ontario (TRCA, 2006) with modeled results from SEDUM. Experimental results showed that the sum of nitrate and nitrite concentrations was 0.251 mgN/L; SEDUM estimated a concentration of 0.197 mgN/L. The difference may be attributable to using average atmospheric concentration data for input into SEDUM instead of ambient concentrations during the time period when the water quality data were taken. The water quality from the control roof at York University had a mean nitrate and nitrite concentration of 0.48 mgN/L. The water quality of the precipitation during the same period was found to be 0.47 mgN/L. While the number of sampled events were limited in this study, it appears that dry deposition of nitrite and nitrate may influence the concentration in stormwater runoff from a conventional roof. An increase in concentration is not observed in the runoff from the green roof.

Table 5.13 Comparison of water quality from a green roof system as determined experimentally and from SEDUM.

Method	**Water Quality from Green Roof (mgN/L)**		**Ratio (SEDUM/ Experimental)**
	Mean	Standard Deviation	
Experimental*	0.251	0.226	--
SEDUM	0.197	0.131	0.79

* mgN/L as nitrate and nitrite from a green roof in Toronto, ON. Ammonia and ammonium are not included here as SEDUM does not account for these.

Based on the water quality verification and comparison to modeled UFORE results, SEDUM appears to capture the significant physical and chemical processes occurring within the green roof system.

5.4. Integration into Economic Cost-Benefit Analysis

Once the model was calibrated and verified against scenarios, the predicted uptake of air pollutants was integrated into the cost-benefit analysis presented in Chapter 4. The rationale was to test whether the SEDUM model was capable of capturing and further constraining the benefits analysis from NOx uptake based on experimental plant data. SEDUM was run according to the conditions used in the experimental results by Morikawa et al (1998) and the assumptions made to extrapolate the uptake per unit area were the same as discussed in Chapter 4. Table 5.14 compares the annual uptake per unit area from both the experimental data and SEDUM output.

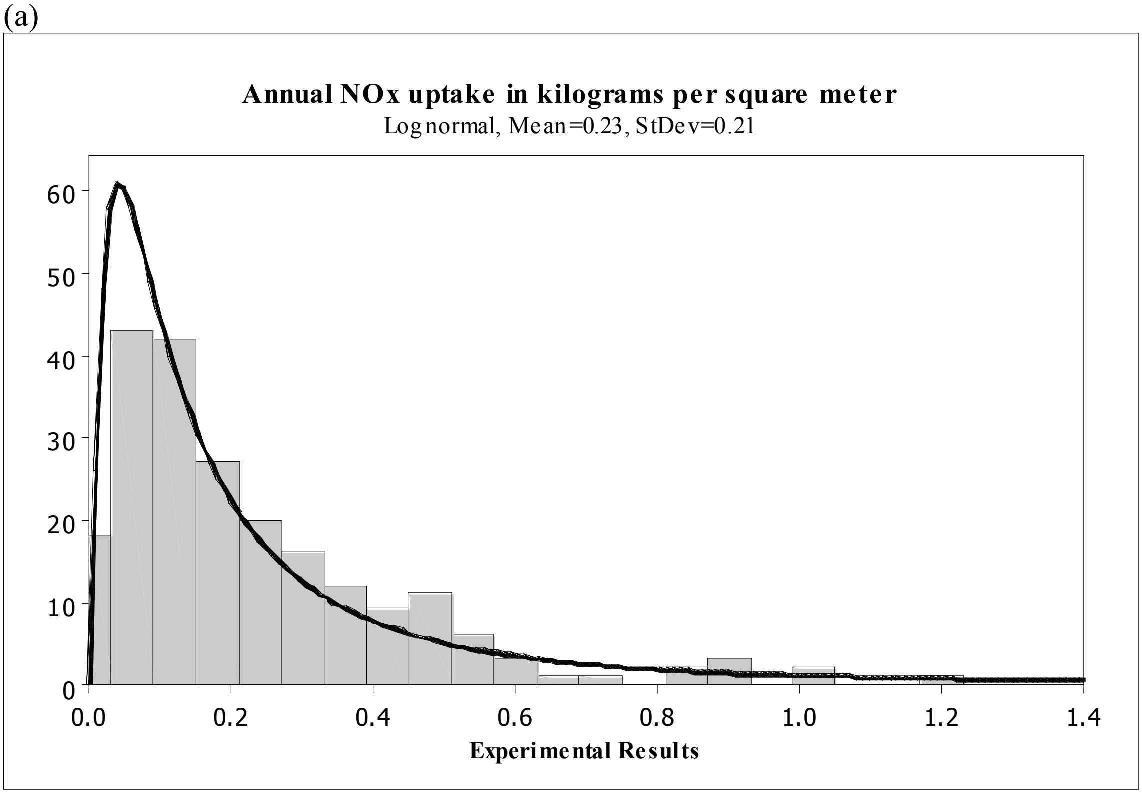
Table 5.14 Comparison of uptake estimates for experimental data (Morikawa et al, 1998) and SEDUM.

Method	**Annual Uptake (kgNO2/m2/y)***		**Ratio (SEDUM/ Experimental)**
	Mean	Standard Deviation	
Experimental	0.27	0.42	--
SEDUM	0.20	0.01	0.74

*Ambient NO_2 concentration of 4.0 mmol/mol.

Based on this analysis, the mean of the SEDUM is 71% of the experimental mean, with a much tighter standard deviation. According to the distributions in Figure 5.3, the experimental data has a wide range of uptake values with a few outliers that shift the mean to the right. While the mean is 0.27 kgNO_2/m2/y, the median uptake is 0.16 kg$_{NO2}$/m2/y. The result from SEDUM is near the median uptake of the experimental data suggesting that SEDUM can capture the uptake potential.

(a)



(b)

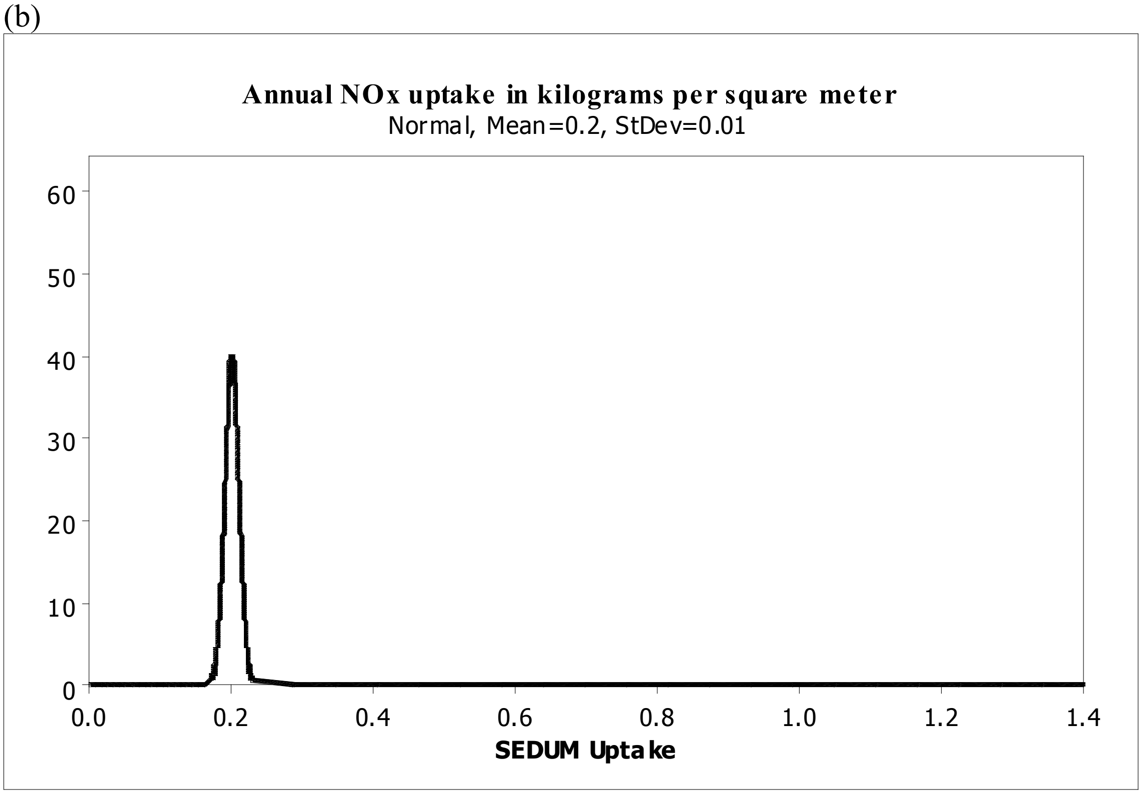


Figure 5.3 Distributions of annual uptake according to (a) experimental results and (b) SEDUM results.

The uptake of reactive nitrogen species as predicted by SEDUM was integrated into the cost benefit analysis. To integrate into the uncertainty analysis, the mean uptake value was used, resulting in an annual benefit between $640 and $2426 for a 2000 m^2 roof. Figure 5.4 shows the net present value (NPV) of the costs of the conventional roof and green roof with SEDUM estimates for air pollution uptake over 40 years.

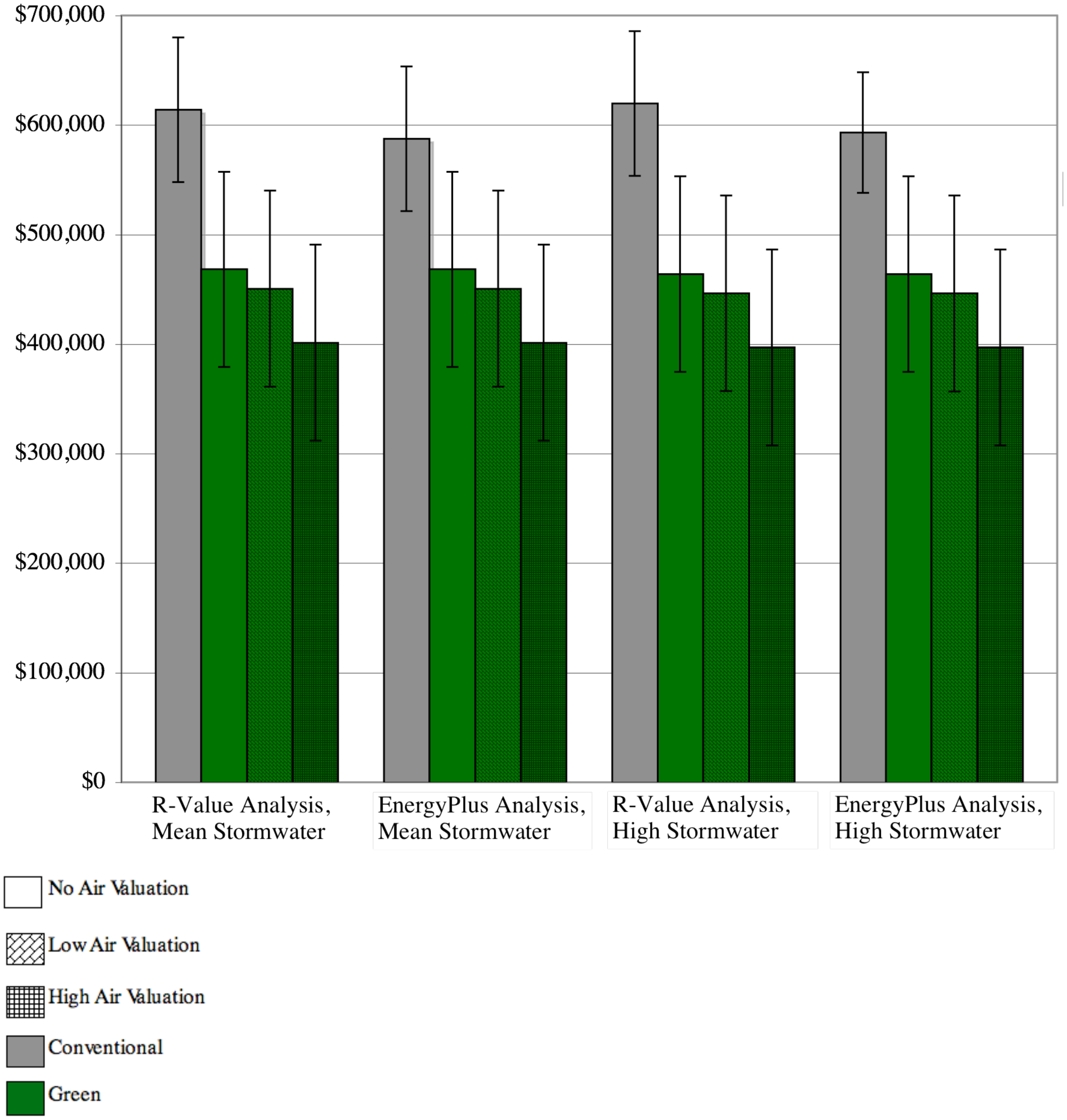


Figure 5.4 Net present value using SEDUM uptake results. Net present value over 40 years of the cost for a conventional roof and a green roof under various valuation and modeling scenarios.

Including air pollution valuation reduces the cost of the green roof system. Table 5.15 presents the NPV over 40 years of the green roof and conventional roof systems.

Table 5.15 Net present value over 40 years for the conventional roof and green roof under various valuations scenarios using SEDUM results.

Valuation Method	Roof Type		Percent change in NPV	SEDUM – Experimental
	Conventional	Green		
R-Value; Mean Stormwater	$613,969	$468,366	23.72	$0
EnergyPlus; Mean Stormwater	$587,465	$468,366	20.27	
R-Value; High Stormwater	$619,828	$463,944	25.15	
EnergyPlus; High Stormwater	$593,324	$463,944	21.81	
Low Air Valuation; R-Value; Mean Stormwater	$613,969	$450,691	26.59	$7,047
Low Air Valuation;EnergyPlus; Mean Stormwater	$587,465	$450,691	23.28	
Low Air Valuation; R-Value; High Stormwater	$619,828	$446,269	28.00	
Low Air Valuation; EnergyPlus; High Stormwater	$593,324	$446,269	24.78	
High Air Valuation; R-Value; Mean Stormwater	$613,969	$401,331	34.63	$26,720
High Air Valuation; EnergyPlus; Mean Stormwater	$587,645	$401,331	31.71	
High Air Valuation; R-Value; High Stormwater	$619,828	$396,909	35.96	
High Air Valuation; EnergyPlus; High Stormwater	$593,324	$396,909	33.10	

Additionally, it presents the cost differential in percent of the conventional roof cost, and as the estimated difference in dollars between the experimental results for uptake according to Morikawa et al. (1998) and the modeled uptake results. Air pollution valuation further reduces the NPV regardless of quantification method. With no air pollution benefit valuation, the green roof is between 20 and 25% less than the conventional roof. With air pollution valuation based on SEDUM, the NPV is between 23 and 36% less over 40 years. Using the SEDUM estimates increases the green roof NPV by $7047 or $26720 depending on the dollar valuation of air pollution mitigation. The annual difference in costs is shown in Figure 5.5.

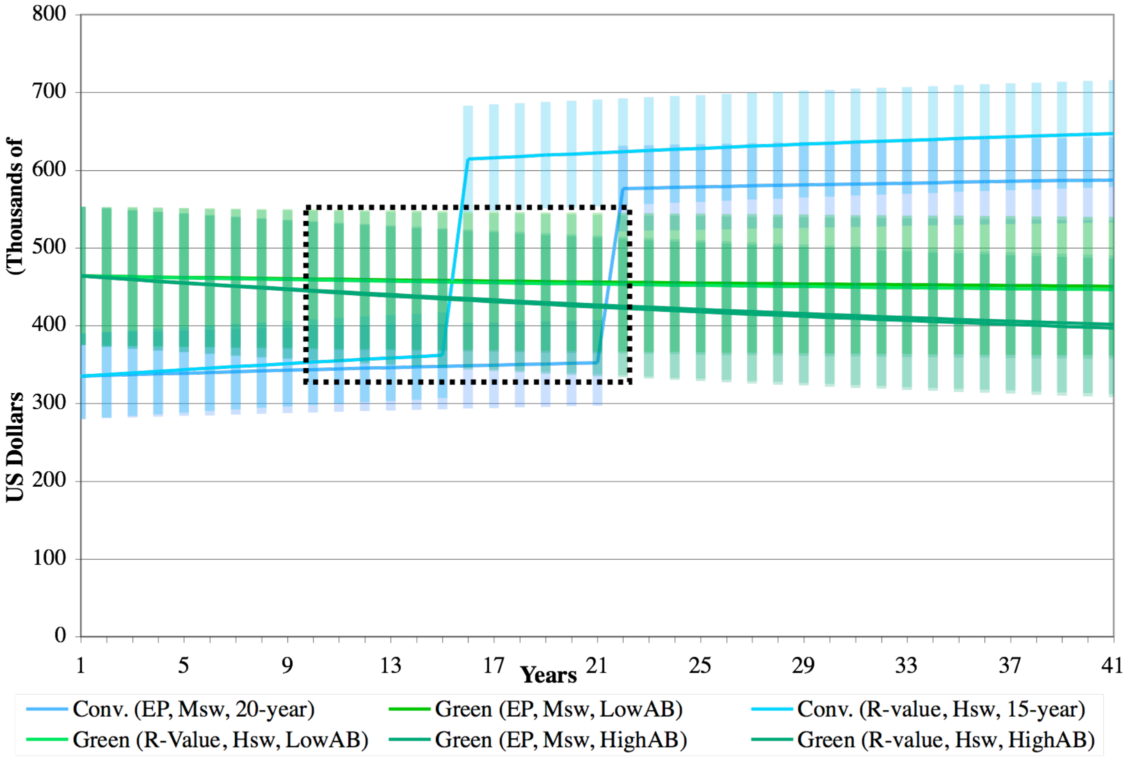


Figure 5.5 Net present value (NPV) from 0 to year t over 40 years under novel methods of valuation (stormwater fees, energy savings, and air pollution uptake) using SEDUM results. The range of the NPV conventional roof costs is bounded according to (i) the mean NPV assuming a 15-year lifetime using the R-Value analysis method for energy expenditure and high stormwater fee, and (ii) the mean NPV assuming a 20-year lifetime using the EnergyPlus model and mean stormwater fees. For the green roof NPV, costs are bounded according to (i) the mean NPV assuming the R-Value analysis method for energy and no fee, and (ii) the mean NPV assuming the EnergyPlus model for energy and 50% reduction in mean stormwater fee. The bars represent one standard deviation above and below the mean. The lower left side of the black box indicates where the lower bound of the green roof NPV is less than the mean NPV of the conventional roof. The upper right side of the black box indicates where the upper bound of the green roof NPV is less than the mean NPV of the conventional roof. The results from SEDUM slightly reduce the slope of the NPV for the green roof scenarios.

The mean green roof breaks even at the year of roof replacement, but the uncertainty bounds show that under a high valuation scenario, there remains the opportunity to break even with the mean conventional roof cost prior to replacement.

5.5.Implications of Design and Environmental Parameters

The rationale for including air pollution valuation is to decrease the time required for the total incurred costs of the green roof to be less than the total incurred costs of the conventional roof. The opportunity for decreasing the NPV of the green roof exists in the design and application of green roof systems.

The location of a green roof affects pollutant uptake. Areas with elevated concentrations of reactive nitrogen species should observe higher uptake on the roof systems until the concentration starts to affect the health of the plant (Wellburn, 1990). Wet-weather should increase the removal rate of reactive nitrogen species; therefore, areas with greater precipitation would see increased uptake potential for green roof systems.

Considering the design parameters, several recommendations can be made to improve uptake of reactive nitrogen species from air. For green roof design, increasing the organic content of soil media, the depth of the soil media, and the density of the soil media will increase reactive nitrogen species uptake. Obviously, the larger the roof area, the greater the uptake potential will be. These design parameters must be weighed against other design constraints including structural load capacity of a roof and the stormwater retention capability of the green roof system. Standards currently exist for soil media density (ASTM E2399-05) and saturated water permeability of drainage media (ASTM E2396-05), which would limit organic content within the media. As such, an addition or revision of existing ASTM standards for green roofs detailing methods for determining air pollution uptake and maximizing uptake may be appropriate. Revisions may be most appropriate within ASTM E2398-05, Water Capture and Media Retention Standards of Geocomposite Drain Layers for Green Roof Systems, and ASTM E2400-06, Standard Guide for Selection, Installation, and Maintenance of Plants for Green Roofs. Both standards could add a section pertaining to design considerations for air pollution mitigation. Alternatively, a new standard may be needed for meeting standards to effectively remove reactive nitrogen species or other compounds from the atmosphere.

Further research into initial concentrations of HNO_3/NO_3-, NO_2, and NO in vegetation could reduce error and provide further insight into plant types with high affinities for atmospheric reactive nitrogen species uptake (Morikawa et al. 2003; Morikawa et al. 2004; Takahashi et al. 2005; Takahashi et al. 2005; Morikawa et al. 2005; Kawamura et al. 2002) that can also survive rooftop conditions. Better understanding of the biogeochemical processes that affect the half-lives of these species can further aid design optimization of the system and may better inform design variables such as soil moisture and plant selection for green roofs.

Chapter 6

Policy Review and Analysis

6.1. Presentation and Description of Results

Chapter 4 and 5 demonstrated that air pollution mitigation via implementation of green roofs is not only technically possible, but also that air pollution uptake and energy efficiency improvements contribute the greatest annual economic benefit to the net present value of green roofs, with stormwater management a distant third benefit. However, current policies aimed towards adoption of green roofs emphasize stormwater quantity reduction. This chapter explores the discrepancy between current policies and green roof technology benefits. First, a review of existing policy frameworks on the adoption of green roofs for private and public sector benefits is presented. Existing US environmental policies are then assessed to determine the extent that they could serve, or be tailored, to promote inclusion of green roofs as a mitigation strategy or a pollutant sink. The feasibility is measured by, and based on, the time required for annual benefits to reduce the net present value (NPV) of the costs of the green roof to that of a conventional roof at year t. This measurement is needed to determine whether the policy accounts for the time constraints placed on private sector decision makers.

6.2. Overview of Current Green Roof Policies

Green roof policies tend to be developed for and are implemented at the municipal level and can be grouped into three categories based on the benefits/incentives they intend to address: **direct or indirect private-sector incentives**, **command-and-control**, and **voluntary measures**. These approaches are used to encourage green roofs for public social benefits and environmental strategies.

6.2.1. Policies Focused on Direct or Indirect Private-Sector Benefits

Private sector benefits from policies can take many forms. These incentives may be granted directly to the building owner or developer, or they may be applied indirectly through a fee or tax reduction. Table 6.1 summarizes various types of incentive strategies (e.g. partial reimbursements, stormwater fee reductions, density bonuses) currently employed by local governments around the world

Table 6.1 Examples of direct and indirect private sector incentives.

Government	Title	Year	Summary
Montreal, Quebec, Canada[a]	Montreal Master Plan	2002	Encourages the installation of green roofs for both the public and private sector. Gaz Metro provides a one-time incentive of $56 Cdn per m^2 of green roof.
Toronto, Ontario, Canada[a]	Green Roof Incentive Pilot Program	2006	Offers a grant of $10 Cdn per m^2 of green roof, up to $20,000 Cdn. Applicants must have at least 50% coverage of the building's roof.
Bonn, Germany[b]	Stormwater Fee	--	Green roof reduces fees by 1.03 €/m^2 annually.
Berlin, Germany[c,d]	Stormwater Fee	1980s	Water utilities established a billing rate including a stormwater fee. In 2004, the stormwater fee was 1.40 €/m^2/y based on impervious surface. Green roofs are not specifically granted a discount. However, if the roof runoff is not connected to a storm drain, then the roof area is not counted as impervious surface. The goal is to control stormwater onsite by integrating green roofs and bioswale technologies into stormwater management.

Government	Title	Year	Summary
Cologne, NRW, Germany[b]	Wastewater Fee Bylaw of 14.12.2003	2003	Stormwater fee of 1.10 €/m^2/y. A sliding scale for green roof fee reduction depends upon the runoff coefficient.
State of North Rhine Westphalia, Germany[b]	Initiative for Ecological and Sustainable Water Management	1999	Green roofs are eligible for 15 €/m^2 subsidy in existing urban areas. Discounts for stormwater fees may also apply. To qualify, the green roof must have a runoff coefficient no less than 0.3, which can be met through independent certification or a minimum depth of 15cm.
Seoul, South Korea[e]	Regulation on the Protection and Promotion of the Green Tract of Land	2002	Preserves green space and promotes greening roofs in the city. The government will contribute up to 50% of the construction cost.
Chicago, Illinois, USA[a]	Building Green/Green Roof Policy	2003	Applies to construction projects receiving public assistance or review by the Department of Planning and Development. Provides incentives that include density bonuses, expedient permit processes, and stormwater retention credit for green roof.
Minneapolis, Minnesota, USA[f]	Code of Ordinance, Chapter 510	2005	Charges property owners a stormwater management fee based on the degree of impervious surface coverage.
Portland, Oregon, USA[a]	Green Building Policy	2001	Encourages green building principles and practices into design, construction, and operations of city facilities, city-funded projects, and infrastructure projects. Evaluates land purchases for future development based upon reducing environmental impacts including transit and bicycle accessibility, urban and brownfields redevelopment, solar access, on-site stormwater mitigation, and vegetation and habitat restoration. New city-owned facilities must include an *ecoroof* (green roof) with at least 70% coverage and include a highly reflected roof material on any non-ecoroof surface. Provides density bonuses and discounted stormwater fees for green roofs.

a (Lawlor et al., 2006); b (Herman, 2003); c (Keeley, 2007); d (Ngan, 2004); e (Koshimizu and Lee, 2007); f (Krause et al., 2007)

In 2001, fourteen percent of all German roofs were green roofs (Herman, 2003). Eighty percent of these roofs were extensive green roofs requiring low investment and maintenance costs (Peck et al., 1999), funded through public and private partnerships. The principal goal of German stormwater management is flood control. Many German towns and cities require rainwater collection basins to control flooding. The expense of collection basins has encouraged the establishment of incentives for green roofs. For example, the state of North Rhine Westphalia pays individuals € 15.00 per square meter for the installation of green roofs. Municipalities have established incentives as well. For example, the town of Esslingen covers fifty percent of the cost of installation, and the city of Darmstadt covers costs up to 5000 € (Herman, 2003). Bonn reduces annual stormwater fees by € 1.03 per square meter for a green roof, and Cologne applies a sliding scale for green roof stormwater fee reductions according to stormwater. The success of these early German incentive programs, led to adoption of incentive policies elsewhere. In the USA, indirect incentives have received greater emphasis than direct incentives with stormwater fee incentives becoming more common as cities switch to a fee based structure for stormwater management (e.g. Minneapolis, Minnesota; Portland, Oregon). Other indirect incentives include density bonuses and expedited permit processing as used in Chicago, Illinois. In other countries, direct financial incentives have greater acceptance (e.g. South Korea, Canada) and include small grants programs or commitments to cover portions of the installation costs.

6.2.2. Command-and-Control Policies

Although rarely used to encourage greening in US cities, in other countries command-and-control greening policies exist to promote a variety of public and environmental benefits. Table 6.2 provides several examples of these strategies.

Table 6.2 Examples of command-and-control greening policies.

Government	Title	Year	Policy/Ordinance/Plan States
Linz, Austria[a]	The Green Space Plan	1985, 2001	Green roofs included in 1985; the 2001 plan requires green roof implementation for new buildings with an area greater than 100 m^2 with a roof slope up to 20 degrees. The roof is required to have 80% green coverage, and the growing medium should be at least 12 cm in depth. For underground parking projects, roofs should be greened by at least 80%, and the growing medium should be at least 50 cm in depth. Projects at grade must be built flush with adjacent properties, and at least 30% of the site should be available for greening over native soil.
Sheffield, South Yorkshire, England[b]	Green Roofs (PUD 8)	2007	Green roofs are required on medium and larger developments (over $1000m^2$) and encouraged on all other developments. Green roofs must cover at least 80% of the total roof area.
Berlin, Germany[c]	Biotope Area Factor (BAF)	--	Legally binding for 13 areas in Berlin. Outside of these areas, the BAF is voluntary. The BAF is a ratio of the ecologically effective surface area over the total land area. Paved or sealed surfaces have a BAF of 0.0 per m2, and green roofs have a BAF of 0.7. New residential projects require a BAF of 0.6, while new commercial projects require a BAF of 0.3.
Osaka, Japan[d]	System to Promote Greening in Sites of a Building	2006	Requires a greenery plan and a statement of the completion of greenery for any new building with an area over $1000m^2$

Government	**Title**	**Year**	**Policy/Ordinance/Plan States**
Tokyo, Japan[d]	Regulation on Protection and Recovery of the Nature in Tokyo	2001	Requires a plan that greens 20% of the site and 20% of the rooftop for any new building with an area over 1000m^2 (privately-owned) or 250m^2 (publicly-owned)
Busan, South Korea[d]	Regulation on Promotion and Support of the Green Roof and Construction	2004	Requires greening 20-30% of roofs for buildings with a site area of 150m^2 (publicly-owned) or 200m^2 (privately-owned).
Switzerland[e]	Federal Law of Switzerland	--	All new or renovated flat roofs must be vegetated. Regulations specify green roof design to maximize biodiversity. Local authorities are required to support endangered species.
Seattle, Washington, USA[f]	Seattle Green Factor	2007	Seattle Ordinance 122311 requires the equivalent of 30% of property in commercial zones to be vegetated. Encourages "vegetative layers" including green roofs, green walls, trees, and water harvesting strategies.

a (Ngan, 2004); b (Government of Sheffield, 2007); c (Berlin, 2007); d (Koshimizu and Lee, 2007); e (Dunnett and Kingsbury, 2004), f (City of Seattle, 2007)

While cities recognize the importance of green roofs, they have different rationales for command-and-control approaches. To encourage green space, Linz, Austria; Osaka, Japan; Tokyo, Japan; and Busan, South Korea require mandatory roof greening for buildings over a specified area (Ngan, 2004; Koshimizu and Lee, 2007). Sheffield has similar requirements with 80% coverage on larger development projects (Government of Sheffield, 2007). Switzerland requires all flat roofs to be greened to increase biodiversity (Dunnett and Kingsbury, 2004). The success of Berlin’s biotope area factor to encourage onsite stormwater management inspired the Seattle Green Factor, a new requirement for landscaping targets in commercial zones using various strategies including green roofs, green walls, trees, and vegetative groundcover (IGES, 2004) City of Seattle, 2007).

6.2.3. Voluntary Green Roof Policies

The third type of existing green roof policy is voluntary. Examples of voluntary approaches are listed in Table 6.3.

Table 6.3 Examples of voluntary greening policies.

City	Title	Year	Policy/Ordinance/Plan States
Brisbane, Queensland, Australia[a]	Strategic & Land Use Planning, Action 13 (Within the Environmental Action Plan)	2007	First city in Australia to include both urban agriculture and green roofs in an action plan to meet predicted global warming climate challenges. A research task force to find solutions to current environmental conditions will develop a package of amendments to City Plan to address policy (e.g. urban agriculture and green roofs).
Vancouver, British Columbia, Canada[b]	Sustainable Stormwater Management Plan	2002	Encourage green roofs to reduce impervious surfaces
Toronto, Ontario, Canada[c]	Official Plan	2002	Supports the development of innovative green spaces like green roofs. Develops "Green Development Standards" to guide the city and private developers to build more environmentally "friendly" projects.
Beijing, China[d]	Beijing's Environmental Construction Plan	2004	Promotes the greening of rooftop areas for the 2008 Olympics to mitigate air pollution, increase indoor humidity, and reduce ambient temperatures.
Tokyo, Japan[e]	Tokyo Green Plan	2000	To increase the amount of vegetation sinks to offset CO2 emissions and alleviate urban warming. Under this plan, mandatory greening requirements for new private and public buildings were passed (see Table 6.2 for details).

a (City of Brisbane, 2007); b (Ngan, 2004); c (City of Toronto, 2007); d (Koshimizu and Lee, 2007); e (IGES, 2004).

Many of the voluntary policies are the first attempt at shaping greening policy for a municipality. Brisbane, Queensland has linked green roofs with urban agriculture as a response to climate change and is presently exploring strategies toward increased adoption of both technologies in urban areas (City of Brisbane, 2007). Air pollution concerns in Beijing have led to commitments for extensive green roofing projects prior to the 2008 Olympics (Koshimizu et al., 2007; Beijing Olympic Games, 2007).

Several cities with established voluntary programs have later added incentive or command-and-control approaches. Toronto, Ontario developed a guide to green development to encourage green projects; this voluntary approach led to a green roof grant project (City of Toronto, 2002; Lawlor et al., 2006). A similar approach was taken in Tokyo, Japan, which first recognized the cooling benefits and CO_2 sequestration capabilities of vegetation prior to adopting mandatory roof greening guidelines (IGES, 2004; Koshimizu et al., 2007).

6.3. Regulatory Analysis

Because the public sector environmental benefits for green roofs are stormwater management and air quality management, the regulatory analysis will focus on municipal and regional management approaches to stormwater and air quality in the US. Municipal strategies at the local level for stormwater management (e.g. fee based structure) are required under the Clean Water Act's National Pollutant Discharge Elimination System (NPDES) permit regulatory structure. National Ambient Air Quality Standards (NAAQS) are set within the Clean Air Act. Regional cap-and-trade programs in place to achieve the NAAQS for ozone are (1) the REgional CLean Air Incentives Market (RECLAIM) and

(2) NO_X Budget Trading Program; both focus on reducing NO_X emissions to meet ozone standards.

Green roofs are incorporated in municipal stormwater policies, but have yet to be included into air emission programs. The stormwater policies included here pertain to the integration of green roofs into the Municipal Separated Storm Sewer System (MS4) program of the NPDES permit regulatory structure. For NO_X emission policy, RECLAIM and the NO_X Budget Trade Program were analyzed to determine if a definitional change or a more significant change or addition would be required to incorporate green roofs. The focus of the analysis for the air emission management programs was the requirement for *best available control technology (BACT)* and the approval process for a technology to be included in these programs.

6.3.1. National Pollutant Discharge Elimination System (NPDES) Stormwater Regulations

The regulation of stormwater falls under the Clean Water Act (CWA), which requires that any generator of point source discharge that has the potential to degrade water quality must apply for a permit under the National Pollutant Discharge Elimination System (NPDES). Initially, stormwater discharges were limited to certain industrial categories (US EPA, 1996). In 1987, the United States Congress added Section 402(p) to the CWA establishing a framework for the US EPA to expand stormwater discharges to include broader source categories under the NPDES program (Dennison, 1996). The regulatory approach required by Section 402(p) was a two-phased approach.

Phase I of the NPDES Storm Water Program was developed in 1990 to address sources of stormwater runoff that had the greatest potential to negatively impact water quality. Phase I permits were issued to municipal separate storm sewer systems (MS4s) serving populations in excess of 100,000 and for discharges associated with industrial activity. There are eleven industrial categories that have stormwater discharges associated with industrial activity, including the following: manufacturing facilities; construction operations disturbing five or more acres; hazardous waste treatment, storage, or disposal facilities; landfills; certain sewage treatment plants; recycling facilities; power plants; mining operations; some oil and gas operations; airports; and certain other transportation facilities (US EPA, 2000). Phase I permits were also issued to facilities where the stormwater discharge contributes significantly to the pollution or impairment of US waters. (Dennison, 1996).

Phase II regulations expanded upon the Phase I requirements to include stormwater regulations for MS4s serving populations less than 100,000 and construction operations disturbing fewer than five acres. Phase II regulations also provide industries the opportunity to be excluded from a NPDES stormwater permit if the facility prevents industrial materials or activities from exposure to inclement weather (US EPA, 2000b). Under Phase II requirements, MS4s must reduce the discharge of pollutants to the maximum extent practicable (MEP) to protect water quality and meet appropriate water quality standards under the CWA (US EPA, 2007a). According to the Michigan Department of Environmental Quality, *maximum extent practicable* is defined as follows:

> "Implementation of best management practices by a public body to comply with an approved storm water management program as required in a national permit for a municipal separate storm sewer system, in a manner that is environmentally beneficial, technically feasible, and within the public body's legal authority," (MDEQ R 323.2161a**)**.

In addition to meeting the MEP, requirements also include the development and implementation of both structural and/or non-structural best management practices

(BMPs). Long-term operation and maintenance of BMPs is also required. Regulatory mechanisms such as ordinances must address post-construction runoff from new development and redevelopment to the extent allowable.

Due to the analytical challenges of detecting (chemical and biological) contaminants in stormwater and mitigation technology challenges to control the large volume of water generated from storm events, most permits have no minimum concentration values that must be met. For impaired water bodies where a total maximum daily load (TMDL) of contaminants has been determined, the NPDES permit will specify numerical standards for stormwater discharge. Permits based on the TMDL for a water body sets contaminant concentration limits for all point sources (e.g. stormwater) and non-point sources (e.g. agricultural sources) of pollution. The NPDES permit is then based on Sections 303(d) of the CWA, which specifies requirements for TMDLs. To reach the standard specified in the permit, treatment may be required prior to discharging stormwater into the impaired water body.

Regardless of treatment requirements, minimizing the area of impervious surfaces can reduce the overall volume of stormwater, which ultimately affects the concentration of contaminants entering surface waters. NPDES permits require facilities to implement traditional stormwater management measures as a means of preventing pollution whenever practicable and appropriate for the site (Dennison, 1996).

Common management measures that control the volume of generated stormwater or filter out pollutants include oil/water separators, vegetative swales, detention ponds, and vegetated roofs. US EPA considers green roofs an innovative best management practice for site plans addressing post-construction stormwater runoff from new development and redevelopment (US EPA, 2007b). As a result, incorporating green roofs into municipal stormwater management plans is straightforward; several cities have developed policies to encourage green roofs through reduced stormwater fees as previously discussed (e.g. Cologne, Germany; Minneapolis, USA). Due to the location-specific differences in policy implementation, the case will be made based on Ann Arbor MI, which is illustrative for policies elsewhere.

Green Roof Integration in NPDES Permit: Ann Arbor, Michigan

When a municipality assesses stormwater fees, they typically are applied according to impervious area. This may be directly applied per area of impervious surface or applied according to a rate. For example, in Ann Arbor, Michigan, the new storm water rate bills property owners according to impervious surface area. These impervious areas include: roofs, paving, sidewalks, structures, gravel driveways, and pools. Rates are set according to residential and commercial property and are due quarterly (City of Ann Arbor, 2007b). For single and two-family residential properties, properties are placed into one of four rate tiers according to total impervious area (Table 6.4).

Table 6.4 Residential Stormwater Fees for Ann Arbor, Michigan (City of Ann Arbor, 2007a).

Impervious Area (m^2)	Stormwater Fee ($ per year)
Up to 203.18	69.84
203.18 to 387.87	103.32
387.87 to 660.54	159.16
Greater than 660.54	259.64

Ann Arbor provides several methods for reducing the stormwater fee. By completing a survey to commit to good stormwater management habits (RiverSafe Home) the residential homeowner saves $4.96 per year. Installing rain barrels on roof downspouts saves $7.16 per year for one to five rain barrels. By creating a rain garden, cistern, or drywell on a property a further $11.20 can be saved per year (City of Ann Arbor, 2007a). Commercial and other properties do not have a tiered fee structure and are billed at a rate of $279.10 per acre per quarter ($279.10 per 0.40 hectare per quarter; $1116.40 per 0.40 hectare annually), plus a $6.30 customer charge per quarter ($25.20 annually) (City of Ann Arbor, 2007c).

Several methods for reducing commercial stormwater fees are also available. Participating in the Community Partners for Clean Streams can reduce the customer charge by 17.3% or $4.36 per year (City of Ann Arbor, 2007c). Installing a stormwater management system that is compliant with the City Code for Stormwater Control (Chapter 63) results in both a fee and charge reduction of 19.5%. Installing best management practices for stormwater reduction such as installation of porous pavement, vegetated swales, constructed wetlands, media filtration, retention ponds, and detention basins can reduce the fee by 6.4% and the customer charge by 17.3%. Green roofs are listed among the approved BMPs (MCCC, 2005).

According to Chapter 29 “Water, Sewer, and Stormwater Rates,” of the City Code, *impervious area* means the following:

> “A surface area which is compacted or covered with material that is resistant to or impedes permeation by water, including but not limited to, most conventionally surfaced streets, roofs, sidewalks, patios, driveways, parking lots, and any other oiled, graveled, graded, or compacted surfaces (Title V, Chapter 29, 2.61(6)).”

As green roofs are not considered conventionally surfaced roofs, they are considered a porous surface by the city (Gih, 2007). Therefore, both commercial and residential property owners can reduce their fees by decreasing their total impervious area through roof greening. Under this assumption, both residential and commercial owners would receive the same “benefit” although financially that benefit would vary as residential rates are tiered while commercial rates are set according to acreage (Gih, 2007). The City of Ann Arbor relies on a computer analysis of infrared aerial photographs to distinguish hard, impervious surfaces in contrast to pervious areas that can absorb stormwater, such as lawns and gardens (and vegetated roofs). Through financial incentive strategies to encourage BMPs and an interpretation of *impervious surface* that excludes green roofs, Ann Arbor was able to integrate green roofs into their stormwater management plans.

6.3.2. RECLAIM: REgional CLean Air Incentives Market

Nitrogen Oxide (NO_X) emissions are regulated under Title IV (Acid Rain Program) and Title 1 (National Ambient Air Quality Standards, NAAQS) of the Clean Air Act (CAA). As ozone is a secondary pollutant of NO_X, several programs have been introduced to reduce NO_X emissions to meet the NAAQS for ozone. Two regional programs exist that seek to address NO_X emissions via market-based approaches. Presently green roofs are not recognized within the market-based programs. The programs were assessed to determine to what extent green roofs could be incorporated and what changes would be needed to incorporate them.

The first urban area emission trade program began in the Los Angeles basin in 1994. The Regional Clean Air Incentives Market (RECLAIM) encourages flexibility for achieving required nitrogen oxide and sulfur oxide emission reductions at facilities within the South Coast Air Quality Management District (Burtraw et al, 2005). The program sets a pollution limit within the region, and allocates credits to facilities, allowing individual facilities to determine what equipment, processes, material, or credits will be used to meet the limits. Annual credits are allocated according to peak production in previous years, existing rules, and control measures. RECLAIM requires annual reductions in the number of total emissions allowances from the program.

While RECLAIM does not formally permit banking, informal temporal trading can occur as allowances are allotted annually on two cycles from July to June and from January to December, and trading can occur between the cycles for a particular year. The program has resulted in reductions of aggregate NO_X emissions from participants by twenty percent below allocations in 2003 (Wallerstein et al., 2005). Between 1994 and 2003, annual NO_X emissions for RECLAIM participants decreased from 25,314 tons to 9,942 tons.

RECLAIM comprises Rules 2000 through 2020 of the South Coast Air Quality Management Districts regulations. Analysis of these rules led to the following three opportunities currently not considered for green roofs: (1) incorporation into the RECLAIM reserve bank; (2) consideration as a best available control technology; and (3) opportunity for emission allowance exchange within a company across multiple facilities.

RECLAIM Reserve Bank

Rule 2020 creates a reserve of NO_X emission reductions that can be used in the RECLAIM Air Quality Investment Program, the mitigation fee program, or for natural gas turbines used during peak hours. Emission reductions are generated by an “emission reduction provider” to be used in the reserve. New methods of emission reduction ceased to be considered after January 1, 2004. To consider a control strategy with the reserve, a proposal must be submitted to the AQMD. The proposal should include a credit generation application form with completed emissions quantification protocol; the total amount of anticipated NO_X emission reductions; cost estimates of implementation calculated in dollars per pound of NO_X emission reductions; and an implementation schedule and timeframe for achieving the emission reductions (Rule 2020, subsection (e), 5). To date, green roofs are not included as an emission reduction technology under this program, and can currently not be considered because of cessation of the 'new methods application'.

Best Available Control Technology

Another potential method for incorporation is under Rule 2005, Requirements for New or Relocated RECLAIM Facilities. A facility permit for a new or relocated facility must include a best available control technology to be applied to every emission source located at the facility. Best Available Control Technology (BACT) is then defined under Rule 1302 (h) of the AQMD regulations as the following:

> "(A) has been achieved in practice for such category or class of source; or (B) is contained in any state implementation plan (SIP) approved by the Environmental Protection Agency (EPA) for such category or class of source; or (C) is any other emission limitation or control technique, including process and equipment changes of basic or control equipment which is technologically feasible for such class or category of source or for a specific source, and cost-effective as compared to AQMP measures or adopted District rules."

Therefore, a green roof could be installed at a point source location and aid in emissions reduction. For this to occur, it must first have previously achieved reductions in practice or be explicitly incorporated into an approved State Implementation Plan (SIP) by the US EPA. The requirements for approval of a SIP will be explored further in the section on the NO_X Budget Trading Program. To qualify as a BACT, green roofs must be shown to be both technologically feasible and cost-effective according to the South Coast Air Quality Management District's (SCAQMD) rules. Chapter 4 discussed the cost effectiveness of green roofs, and if further investigation of the economics according to SCAQMD procedures suggested an economically favorable alternative to conventional pollution abatement, the green roofs may qualify as a BACT for inclusion under RECLAIM.

External Offsets and Emission Reduction Credits (ERCs)

One final method for green roof incorporation into RECLAIM is through serving as the external offset for a facility. An *external offset* allows for an emission increase at a facility if an emission reduction occurs at an alternate facility. For the emission reduction to count as an emission reduction credit (ERC), the reductions must be demonstrated to be real, quantifiable, permanent, federally enforceable, and not greater than what could be achieved through use of current BACT (Rule 1309 (b)(4)). These reductions can occur assuming that (1) both facilities are within the same air basin; (2) the ERCs are generated upwind of the emission increase, and the air quality upwind is in a worse non-attainment status than the downwind basin; or (3) the ERCs are generated upwind from the emission increase, and the air quality downwind is significantly affected by emissions in the upwind basin (Rule 1309 (i)(2)).

There are certain limitations to participation in RECLAIM (Rule 2001, subparagraph (i)(1)(A-J)). The following facilities are prohibited from entering RECLAIM: dry cleaners; fire stations; landfill gas control operations or energy recovery facilities; facilities that switched to only electric power prior to October 15, 1993; police stations; public transit; restaurants; potable water operations; facilities that have ceased to operate prior to January 1, 1994; and those facilities in the Riverside County portions of the Salton Sea and Mojave Desert Air Basins (unless adhering to Rule 2001, subparagraph (i)(2)(M), see next paragraph).

Certain types of facilities were initially excluded from RECLAIM but can elect to enter the program if an application is submitted, the facility does not have an Order of Abatement or is not in violation of any AQMD rule, and the facility is not required to meet a compliance date within six months of submission of the application. These facilities include the following: equipment rental facilities; facilities with "various location" permits; hospitals; prisons; publicly owned municipal waste-to-energy facilities and sewage treatment facilities; portions of facilities conducting research; schools or universities; publicly owned and operated electric power generating systems in Burbank, Glendale, or Pasadena; ski resorts; facilities on San Clemente Island; electric generating facilities located in the Riverside County portions of the Salton Sea or Mojave Desert Air Basins (for NO_X emissions only); and facilities that are agricultural sources (Rule 2001, subparagraph (1)(2)(A-N)). <u>These approved facilities if within RECLAIM could benefit from the inclusion of green roofs as either a BACT or employ the technology on their roofs to qualify for an emission offset</u>.

6.3.3.6.3.3. NO_X Budget Trading Program (NBP)

While the Los Angeles basin struggles to meet NAAQS for ozone due to local emissions becoming trapped by an air inversion layer that frequently develops locally (Burtraw et al, 2005), long-range transport of nitrogen oxides can lead to ozone non-attainment for areas downwind of emission sources. After previous attempts to address this phenomenon in the northeast corridor of the US with mixed results (see Chapter 2 for greater detail), in 2003 the NOx SIP (State Implementation Plan) Call was established (US EPA, 2003). Originally, this program targeted 22 states accounting for 90% of boilers covered in the Title IV program, but currently has 19 states participating. The NO_X SIP Call provided states with the flexibility to meet emission targets including the option to participate in the NO_X Budget Trading Program (NBP) (US EPA, 2004). Regionally, this program expects to reduce 2007 emissions by 34% from a baseline of 3.51 million tons and summertime emissions by 62% from a baseline of 1.5 million tons. These reductions will reduce national emissions by 22% of the 5.4 million ton baseline in 2007 and summertime emissions by 40% of 2.4 million tons in 2007 (Burtraw et al, 2005).

Relevant SIP Definitions

The NO_X Budget Trading Program is for point source emissions and sets definitions according to those within the NO_X SIP Call. As a result, this analysis focused on the regulations for approval of the State Implementation Plan as required by US EPA. Title 40, part 51 of the Code of Federal Regulations (CFR) details the requirements for developing and submitting an implementation plan for state agencies. The requirements include definitions as defined in the federal regulations that may be revised only if the state uses a more stringent definition.

According to 40 CFR 51.100 (n), a *control strategy* seeks to reduce emissions to meet national air quality standards. As part of a control strategy, a state can employ various measures including controlling emissions; using market-based approaches to encourage reductions; closing facilities or changing operations; inspecting vehicles; and controlling fuel or additives used in vehicles. The SIP is required to describe enforcement measures for control strategies including procedures for monitoring, handling violations, and establishing an enforcement agency (40 CFR 51.121 (f)).

According to 40 CFR 51.165 (a)(1)(xl), *best available control technology* (BACT) is defined as the following:

> "… an emissions limitation (including a visible emissions standard) based on the maximum degree of reduction for each regulated NSR [new source review] pollutant which would be emitted from any proposed major stationary source or major modification which the reviewing authority, on a case-by-case basis, taking into account energy, environmental, and economic impacts and other costs, determines is achievable for such source or modification through application of production processes or available methods, systems, and techniques, including fuel cleaning or treatment or innovative fuel combustion techniques for control of such pollutant. In no event shall application of best available control technology result in emissions of any pollutant which would exceed the emissions allowed by any applicable standard under 40 CFR part 60 or 61. If the reviewing authority determines that technological or economic limitations on the application of measurement methodology to a particular emissions unit would make the imposition of an emissions standard infeasible, a design, equipment, work practice, operational standard, or combination thereof, may be prescribed instead to satisfy the requirement for the application of BACT. Such standard shall, to the degree possible, set forth the emissions reduction achievable by implementation of such design, equipment, work practice or operation, and shall provide for compliance by means which achieve equivalent results."

Similarly to the findings from the RECLAIM rule analysis, a green roof system has the potential to become a BACT if the technological and economic limitations would make adoption of the technology feasible. The challenge for incorporating green roofs would be to establish methods for monitoring the uptake capacity of these roofs. Results presented in Chapter 5 serve as a starting point by modeling the uptake potential of green roof systems.

Limitations to Emission Reduction Credits (ERCs)

Section 40 CFR 51.121 of the SIP summarizes the revision requirements as related to nitrogen oxide emissions. It provides mechanisms to limit the value of ERCs or banked allowances, which could limit the extent of green roof adoption within a market context. If ERCs exceed a 10% threshold above the total allowable emissions during the ozone season, then the number of credits that can be used per ton of nitrogen oxides emitted are limited according to the following equations as stated in 40 CFR 51.121 (b)(2)(ii):

$$\text{Ratio} = 0.10 \cdot \frac{\sum \text{Allowable NO}_{\text{X}} \text{ Emissions}}{\text{Total ERCs}} \tag{6.64}$$

$$\text{ERCs}_{\text{Usable by Facility A}} = \text{Ratio} \cdot \text{ERCs}_{\text{Facility A}} \tag{6.65}$$

The ERCs in Equation 6.2 that Facility A can use have a value of 1 credit per 1 ton (0.907 Mg) of nitrogen oxides emitted. All additional ERCs must be used at a minimum of 2 credits per 1 ton (0.907 Mg) of nitrogen oxides emitted. A limitation is also placed upon facilities with ERCs that exceed 10% of the source's allowable emissions. Only ERCs up to 10 percent of the allowable emissions may be used at the rate of 1 credit per ton (0.907 Mg). Additional ERCs can only be used at a minimum rate of 2 credits per 1 ton (0.907 Mg).

If the ability for green roofs to serve as an abatement technology can be quantified and monitored to show the extent of uptake during the ozone season, then it appears that green roofs could be incorporated as a BACT within the emissions framework.

6.4. Scenario Development to Assess Green Roof Policy Opportunities

This section will utilize the net present value (NPV) of green roof systems to explore the potential value of annual policy incentives. Previously, it was shown that the over the lifetime of the green roof, the net present value is 20 to 25 percent less than that of the conventional roof (see Chapter 4 for analysis). This was shown to be highly dependent on the condition that the green roof lasts longer than the conventional roof, which has been shown in practice (Köhler, 2006). As private-sector decision-makers often focus on short time horizons for a return on investments, applying market-based incentives to reduce the time required for the NPV of the costs of a green roof to equal the NPV of the costs of a conventional roof may serve as an effective policy to encourage green roof technology.

The required annual market-based incentive was determined for the net present values of the green roof and the conventional roof to be equal considering a time horizon of 5, 10, 15, and 20 years. Table 6.5 summarizes the assumptions used in this analysis (see Chapter 4 for further detail).

Table 6.5 Economic parameters for the cost benefit analysis of a 2000 m^2, one-story building in Ann Arbor, Michigan.

Parameter	Value	Source
Mean Conventional Roof Cost	\$335,000 ± \$55,072	(Clark et al., 2007)
Mean Green Roof Cost	\$464,000 ±\$89,138	Clark et al, 2007
Present Value Energy Costs using EnergyPlus	\$710	Clark et al, 2007
Present Value Energy Costs using R-Value Analysis	\$1,670	Clark et al, 2007
Interest Rate	5%	US Federal Reserve, 2007
Inflation Rate	3%	US DOL, 2007

The energy costs were determined according to two modeling methods. EnergyPlus, version 2.0, is a building energy simulation program based on DOE-2 and supported by the US Department of Energy. The R-Value analysis is a simple 1-dimensional energy model. A comparison of these models is presented in Chapter 4. Additional assumptions include replacement of a conventional roof at year 20, and the exclusion of maintenance costs. See Chapter 3 for a detailed methodology for the NPV analysis.

The analysis assessed policy incentives according to three scenarios. Scenario 1 determined the required reduction in stormwater fee per square meter of green roof. Scenario 2 determined the market-based incentive per metric ton of NO_X taken up by the green roof system assuming an annual uptake of 0.19 kg/m^2 as determined in Chapter 5. The final scenario combined both types of market-based incentives to assess an integrated environmental policy approach assuming the burden is split evenly between the two policies. The purpose of this analysis is to inform policymakers of the minimum value for incentive strategies to close the mean cost differential between the conventional roof and the green roof system within a private sector decision-making time horizon.

6.4.1. Scenario 1: Stormwater Valuation

The NPV analysis was performed, and the required stormwater fee savings per square meter were determined according to the year where the NPV of the green roof system and the conventional roof system would be equal (fixed at 5, 10, 15 and 20 years). The outcome of the NPV analysis represents the incentive per area of roof greened required to make the green roof competitive within 5, 10, 15, and 20 years (Table 6.6).

Table 6.6 Annual incentive requirement for stormwater fees for mean green roof cost competitiveness under various time horizons.

Time horizon (years) for NPV parity	Policy 1: Stormwater $/m^2 R analysis	Policy 1: Stormwater $/m^2 EP analysis
5	12.84	13.32
10	6.33	6.81
15	4.17	4.65
20	3.09	3.57

Presently, no stormwater fee incentive programs meet these minimum rates. A survey of US municipal stormwater fees found an average rate of $0.17 per m^2 of impervious surface (refer to Chapter 4). Considering a full fee reduction for Ann Arbor (assuming that greening 2000 m^2 would drop the impervious surface area to a lower total acreage), the reduction only provides $0.56 per m^2. Stormwater fees in Germany are only 49 to 66 percent of the lowest rate for a 20-year payback. The prices for green roofs in Germany are considerably less than prices in the US due to the maturity of the industry and economies of scale; therefore, the success of their programs cannot be directly applied to US programs (Philippi, 2007). The current available stormwater pricing strategies are insufficient to overcome the cost differential in the US green roof industry within a time horizon that would be attractive to developers.

6.4.2. Scenario 2: Air Pollution Valuation

The same analysis was conducted to determine minimum price for emission reduction credits (ERCs). As these are traded in the US, results are reported in Table 6.7 in dollars per metric ton.

Table 6.7 Market price for NO_X emission allowances necessary for mean green roof cost competitiveness under various time horizons.

Time horizon (years) for NPV parity	Policy 2: Air Pollution \$/Mg R analysis	Policy 2: Air Pollution \$/Mg EP analysis
5	6.76E+04	7.01E+04
10	3.33E+04	3.58E+04
15	2.19E+04	2.45E+04
20	1.63E+04	1.88E+04

All of these values exceed the estimated public health benefit of NO_X pollution reduction between \$1680 and \$6380 per Mg (US EPA, 1998). For the NBP, there was a price drop from \$3860 per Mg toward the beginning of 2005 to \$660 per Mg by the middle of 2007[1]; both values are below the necessary prices provided in Table 6.7. For the 2006 season under RECLAIM, the average price depending upon the emission year ranged from \$2594 per Mg for 2005 ERCs to \$15,866 per Mg for 2008 ERCs and \$17,308 per Mg for 2010 ERCs. The price for 2010 exceeded a regulatory price control of \$15,000 per ton (\$16,538 per Mg), which is the upper limit for the RECLAIM market. The RECLAIM price control limits the market from reaching the price per Mg necessary as listed in Table 6.7. Under RECLAIM, the market price is at a rate that would reduce the time required for a green roof to be cost competitive with a conventional roof.

6.4.3. Scenario 3: Integrated Policy Approach

Presently, indirect incentives based on stormwater fees are not priced at an appropriate rate to reduce the time required for the NPVs to be equal. Under the

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[1] This volatility is a result of several factors. Fewer emissions were generated in the 2006 ozone season as a result of an increased reliance on gas turbines (lower prices for natural gas) for electricity generation. In 2007, Missouri entered the NBP and was predicted to bring additional allowances into the market. The transition of NBP to fall under CAIR allows for the transfer of banked emissions, and market responded by further reductions in the price of allowances (US EPA, 2007).

RECLAIM program, if green roofs were accepted as a method for NO_X abatement, the NPVs could be equal at year 20 prior to roof replacement. Scenario 3 explores pricing under an integrated approach. Assuming an equal financial burden for stormwater fees and air pollution mitigation, Table 6.8 displays results from the analysis.

Table 6.8 Annual incentive requirements when stormwater fees and market-based emissions programs are collectively used to reduce the time horizon.

Time horizon (years) for NPV parity	Stormwater \$/m2 R analysis	Stormwater \$/m2 EP analysis	Air Pollution \$/Mg R analysis	Air Pollution \$/Mg EP analysis
5	6.42	6.66	3.38E+04	3.50E+04
10	3.16	3.40	1.67E+04	1.79E+04
15	2.08	2.32	1.10E+04	1.22E+04
20	1.55	1.79	8.13E+03	9.40E+03

While the stormwater management fees remain above those currently in place in many US municipalities, the annual rate for achieving equal NPVs by year 15 or 20 is in line with rates in place in several communities in Germany. Similarly, the market-based price presently traded under RECLAIM does meet the required price for NPV equality by year 15 and 20. The historic price for the NBP and the recent volatility remain below the required price. The public health benefits as valued by EPA are also below those prices. Together, it is possible for current incentive approaches offered by market-based stormwater and air policies to further reduce the time required for the green roof NPV to equal the NPV of the conventional roof beyond the roof replacement factor.

This analysis focused on the mean costs of extensive green roof and conventional roof systems. If the cost of green roofs can be reduced, the requisite incentive price can also be reduced. Considering an installation cost that is one standard deviation below the mean green roof cost would reduce the incentive price considerably as shown in Table 6.9.

Table 6.9 For a green roof priced 1 standard deviation below the mean, annual incentive requirements when stormwater fees and market-based emissions programs are collectively used to reduce the time horizon.

Time horizon (years) for NPV parity	Stormwater \$/m2 R analysis	Stormwater \$/m2 EP analysis	Air Pollution \$/Mg R analysis	Air Pollution \$/Mg EP analysis
5	1.70	1.94	8.94E+03	1.02E+04
10	0.69	0.93	3.64E+03	4.90E+03
15	0.36	0.60	1.88E+03	3.14E+03
20	0.19	0.43	1.00E+03	2.26E+03

Under an integrated policy scenario, the current full fee reduction for Ann Arbor (\$0.56 per m^2) in combination with ERCs for air pollution mitigation would reduce the time horizon to at most 15 years. Considering air pollution ERCs from the RECLAIM program alone with a reduced roof price could result in a time horizon of less than 10 years (\$7280/Mg_{NO2} using R-Value analysis and \$9800/Mg_{NO2} using EnergyPlus). Opportunities to reduce the upfront cost of extensive green roof systems could significantly reduce the time to NPV parity.

6.5. Summary and Opportunities

The regulatory analysis showed that it is possible to integrate green roofs into existing regulatory programs. Currently, the NPDES stormwater program includes green roofs within the definition of best management practices, and as a result, several municipalities have incentives in place for green roofs. Sampling methods for quantification and monitoring of air pollution uptake are needed prior to adoption into market-based air programs. For air pollution mitigation, if the ability for green roofs to serve as an abatement technology can be quantified and monitored to show the extent of uptake during the ozone season, then it appears that green roofs could be incorporated as a BACT within the NO_X SIP Call and RECLAIM. In addition to qualification as a BACT, RECLAIM could also incorporate green roofs as an emission offset.

Incorporating the incentive approaches into a net present value analysis for the green roof system revealed that employing incentive strategies according to a single environmental benefit at the current rate of incentive measures has limited affect on the time required for the NPV of the mean costs of the conventional and green roof systems to be equal. Reducing the upfront cost would increase the affect of a single or multiple incentive policy approach.

However, when policy strategies include both stormwater and air quality incentives, the time horizon can more easily be reduced under current incentive strategies. Strategies for further reduction can include increasing the financial incentive for stormwater or air pollution although it should not be extended beyond the public health value. While this value is available for NO_X pollution reduction, further research into stormwater infrastructure management costs need to be undertaken to determine whether municipalities are appropriately valuing stormwater volume reduction.

Efforts to improve plant selection for air pollutant uptake could reduce the price required per Mg of NO_X and is being explored in the phytoremediation field (Takahashi et al, 2005) and developed for the green roof industry (The Japan Times, 2005). Soil media design changes including increasing the density and organic carbon content as suggested in Chapter 5 could further improve NO_X uptake. It is worth noting that market-based approaches to air pollution management are not limited to nitrogen oxides, and incorporation of green roofs into sulfur oxide, mercury, or VOC markets could reduce the discrepancy between the current market-price and the needed market-price for reducing the time to NPV parity.

Chapter 7

Conclusions and Future Directions

7.1. Summary

As the world continues to urbanize, the resulting growth and horizontal expansion of cities stress private and public utilities. Multi-faceted and scalable solutions such as green roofs are needed to temper the environmental impacts of stormwater and energy emissions management in growing cities. Some of the challenges facing widespread integration of green roofs include (i) their premium cost over conventional roofs, (ii) quantitative uncertainty about their benefits (e.g. air pollution mitigation, energy benefits, stormwater quantity reduction and quality of runoff, and (iii) the design of policies aimed at incentivizing private and public building owners. The goal of this dissertation was to develop an engineering analysis-based policy tool for green roofs as a pollution abatement technology. The governing hypothesis for this research is that the business case for green roofs can be made by the integration of green roofs as a pollution abatement technology into an emissions market scenario.

While other countries have succeeded in encouraging the technology through command-and-control approaches, the internal rate of return on the investment is poorly quantified and highly dependent on local assumptions and negotiations for market-based strategies to significantly impact adoption rates. A comprehensive quantitative analysis of green roof benefits indicates that there is opportunity for green roof technology to mitigate air pollution (using NOx compounds as a proxy), provided this public benefit can be transferred to the building owner through financial incentives or integration into market-based emissions management policies. Central to this new framework is the rigorous quantification of the extent of air pollution mitigation, to inform policy design and identify opportunities in existing market-based air policies.

7.2. Specific Contributions of Research

This section details how the specific contributions of this research have contributed to the knowledge gaps and objective identified in Chapter 2, which was capture in the following statement:

> *"The development of a quantitative and probabilistic framework for assessing of the fate of these contaminants in green roofs systems is the first step to quantify their economic impact, and to explore possible policy designs for their integration in clean air policies."*

7.2.1. Environmental Cost-Benefit Analysis

The economic opportunity for air quality management through green roofs within the context of all other quantifiable environmental benefits (stormwater, energy savings) was explored at the individual building scale (2,000 m^2). Upfront capital investment in an extensive green roof system costs on average 39% more than a conventional roof system. Whereas currently the incentive for green roofs is based on their reduction of stormwater volume, this research showed that this economic benefit does not make the business case for green roofs. Energy savings from insulation, beneficial health impacts from reduced air pollution, and added roof longevity are the economic drivers for this technology. The 40-year green roof NPV is less than the conventional roof, with an opportunity to break even in the 13-23 year timeframe. Proper valuation of environment benefits can further reduce the net present value of a green roof and promote long-term investment.

7.2.2. Multimedia Environmental Fate and Transport

To translate public health benefits of NO_X reduction to the private sector, the extent of air pollution mitigation by green roofs must be understood. To this end, the project developed a rigorous probabilistic approach to quantify the fate and transport of nitrogen oxides, which are primarily emitted by vehicles and the electric utility industry.

A custom fugacity-based modeling tool (SEDUM) was developed to incorporate soil and plant uptake, as well as contaminant concentrations in stormwater runoff. This model was applied to quantify the uptake capacity of green roofs and yield information on potential stormwater impacts by atmospheric-borne reactive nitrogen species. Accounting for both dry and wet deposition and multiple forms of reactive nitrogen species, SEDUM showed that green roofs have the potential to take up 0.19 ± 0.01 $kg/m^2/y$, translating into annualized benefit between \$640 and \$2426 per year for a 2,000 m^2 green roof. In general, vegetation incorporates 2.1 to 2.7 times more reactive nitrogen species than estimated by models that focus on dry deposition and nitrogen dioxide, such as the USDA UFORE model. The green roof fate and transport simulator further allowed for probabilistic testing (by coupling Monte Carlo type simulations to SEDUM) of green roof input variables. This analysis provided a subset of design optimization parameters aimed at pollutant uptake efficiency, based on solid media properties (composition, porosity, depth), climate and air quality characteristics of relevance to the green roof design community and property developers.

7.2.3. Policy Analysis and Opportunity Assessment

The current state of green roof policy, and US stormwater policy, were assessed for their potential to encourage the adoption of green roofs for stormwater quantity reduction and quality improvement. US air emissions policies were evaluated to explore the opportunity for scientifically-informed and economically advantageous integration of green roofs to market-based air emissions mitigation policies. While command-and-control approaches exist in the US (see Seattle's Green Factor requirement for commercial development), most programs are voluntary with indirect financial incentives. Many of these financial incentives focus on stormwater, which has led US EPA to consider green roofs as a BMP. Further evidence and ease of measuring technology is required for incorporation into current emission trade programs. For a 10 year time horizon, stormwater fees would need to be between \$6.33/m^2 and \$6.81/m^2 for the current mean cost of a green roof (mean stormwater fee savings are presently at \$0.17/m^2). For air incentive strategies, a 10 year time horizon at present costs and present uptake potential would require a market price of \$33,300 to \$35,800 per $\mathrm{Mg_{NOX}}$. Only when used in tandem do the required benefits can stormwater fees and $\mathrm{NO_X}$ market-based emission credits reduce the time required to reach NPV parity. Future reductions in cost of green roof implementation would bring the time horizon within 10 years.

7.3. Future Directions

While incentive strategies and pricing schemes for policy were explored in this work, further research efforts could explore external economic factors in greater detail. Potential directions with an economic focus are summarized below.

- **Reductions in upfront cost**. Installation cost reductions may occur according to regional variations in salary for installers and may reduce overall as the industry matures, laborers become more familiar with the technology, and as technological improvements occur.
- **Financial accounting of additional upfront costs.** The analysis presented here used a discount (interest) rate of 5 percent. Typically, purchases for building structure are discounted over the lifetime of the building (39 years). Tangible personal property can be depreciated over a much shorter period, 5 years. *Hospital Corp. of American v. CIR* held that tangible personal property may include property such as carpeting, vinyl wall and floor coverings as these properties are not necessary for the building structure and are designed for removal or replacement at regular intervals. Green roofs may also fall under a similar category or could be designed to meet such guidelines for *tangible personal property*. Classification as personal property and consideration of additional methods of financial accounting could improve the economic case for green roofs.
- **Energy price fluctuations**. Future energy prices are also uncertain, and price increases due to CO_2 taxation or other regulatory strategy could further improve the valuation of energy savings realized from a green roof (see Appendix 1 for preliminary work).

With the quantitative assessment and policy evaluation framework in place, it is now possible to probe key questions aimed toward the implementation and location/design-specific benefit assessment of green roofs. These topics are summarized briefly here and are explored in greater detail in the appendices:

- S**calability of economic and environmental benefits**. Public benefits may be more appropriately evaluated at larger scales. Large-scale (e.g. neighborhood, city, metropolitan area) greening of urban roof area has the potential to result in secondary and tertiary effects to a city's climate and energy-based emissions. Large-scale greening may also affect stormwater management through peak flow reduction and delays in stormwater runoff.
- **Design parameters** of soil media and vegetation. SEDUM indicated that increasing the organic content of soil media, the depth of the soil media, and the density of the soil media are key design parameters involved in increasing reactive nitrogen species uptake. Further analysis could explore fate and transport of nitrogen species and additional contaminants within the soil media in greater detail. Future work could also consider specific plant species uptake performance.
- **Effects of green roofs on urban tropospheric chemistry.** Introduction of vegetation at larger scales can change the surface albedo, humidity, and introduces biogenic volatile organic compounds (BVOCs) within the community (Rosenzweig et al., 2006). These changes alter the rates and paths of atmospheric chemical reactions in a local airshed. Further research into the effects of large-scale urban greening should explore these complexities.

Translating the key research needs highlighted here into economic terms will inform designers in the optimization of green roof systems, and aid the public sector in developing appropriate policies for proper valuation to encourage this technology to address the multi-faceted environmental problems that impact urban areas.

Appendix 1

Effects of Energy Prices on the Green Roof Net Present Value

In the analysis detailed in Chapter 4, it was assumed that annual energy inflation occurred at the same rate as stormwater fees and roof installation. A rate of three percent was used according to the 2005 to 2006 Consumer's Price Index (CPI) (US DOL, 2006). In recent years, energy prices have inflated much faster than the rate listed by the CPI. An article in *The Economist* estimates that pricing CO2 emissions at $50 per Mg would increase petroleum prices and electricity prices. Assuming that the 15% increase in petroleum prices would translate to similar increases in natural gas for heating, and the 35% increase in electricity prices would apply to coal-fired generation, increased savings from energy costs could be realized by employing green roof technology (Cleaning up, 2007).

In Chapter 4 under standard energy inflation, the NPV of the green roof was between 20.3 and 25.2 percent less than the conventional roof over 40 years considering only stormwater fees and energy savings with the difference in calculation of energy savings accounting for greater variation than the difference in calculation of stormwater fee savings (Figure 4.3, Table 4.3 see Chapter 4). If CO2 emissions are taxed at $50 per Mg or a similar increase in energy prices occur, the NPV of the green roof will further decrease. Figure A1.1 and Table A1.1 reveal that the percentage savings in the NPV over 40 years increases to 21.0 to 28.9 percent less than the conventional roof when considering energy savings and stormwater fees.

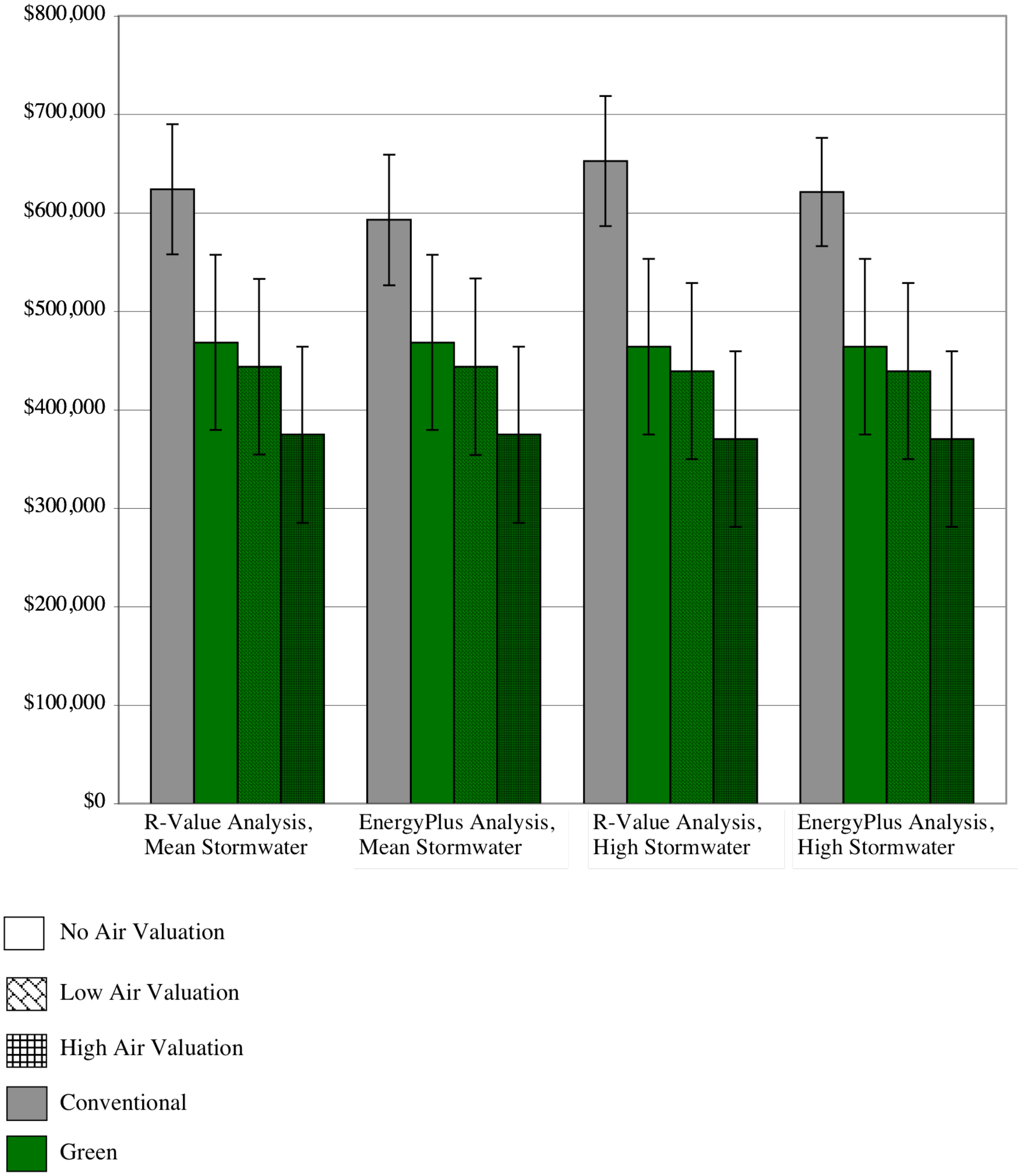

Figure A1.1 Net present value over 40 years under CO2 energy taxation policy.

Table A1.1 Summary of net present value under various scenarios according to CO2 taxation energy policy.

Present Value at 40 years	Roof Type		Percent change in NPV
	Conventional	Green	
R-Value; Mean Stormwater	$624,056	$468,366	24.95
EnergyPlus; Mean Stormwater	$592,758	$468,366	20.99
R-Value; High Stormwater	$652,482	$463,944	28.90
EnergyPlus; High Stormwater	$621,185	$463,944	25.31
Low Air Valuation; R-Value; Mean Stormwater	$624,056	$443,644	28.91
Low Air Valuation;EnergyPlus; Mean Stormwater	$592,758	$443,644	25.16
Low Air Valuation; R-Value; High Stormwater	$652,482	$439,222	32.68
Low Air Valuation; EnergyPlus; High Stormwater	$621,185	$439,222	29.29
High Air Valuation; R-Value; Mean Stormwater	$624,056	$374,611	39.97
High Air Valuation;EnergyPlus; Mean Stormwater	$592,758	$374,611	36.80
High Air Valuation; R-Value; High Stormwater	$652,482	$370,190	43.26
High Air Valuation; EnergyPlus; High Stormwater	$621,185	$370,190	40.41

Appendix 2

City Scale Economic and Environmental Benefit Analysis

While this research focused on quantifying the environmental and economic benefits at the building scale, public benefits are more appropriately evaluated at larger scales. Large-scale (e.g. neighborhood, city, metropolitan area) greening of urban roof area has the potential to result in secondary and tertiary effects to climate and emissions. For example, decreasing urban temperatures in neighborhoods may alter energy demand, which could contribute to reductions in the atmospheric emissions of a region

Preliminary assessment of the scalability of benefits was conducted using a city-wide greening analysis based upon two US cities (Chicago, Illinois and Detroit, Michigan). As total roof area data are unavailable for most cities, values were estimated by extrapolating roof area estimates obtained for Sacramento, California (Akbari et al., 2003). In that study, the authors used high-resolution orthophotos to link roof area to land use zones (residential, commercial, industrial). For the purpose of this study, the percentage roof area per land use zone in Sacramento was extrapolated to the Chicago and Detroit metropolitan areas. Chicago metropolitan land use data were aggregated from data sets provided by the Northeastern Illinois Planning Commission (1995). For the Detroit metropolitan area, the individual county datasets were merged prior to accessing land use data for the region (SEMCOG, 1995). For this analysis, areas were ignored if they fell outside of residential, commercial, or industrial land use zones or were primarily composed of undeveloped or minimally developed land (Figure A2.1 and Figure A2.2).

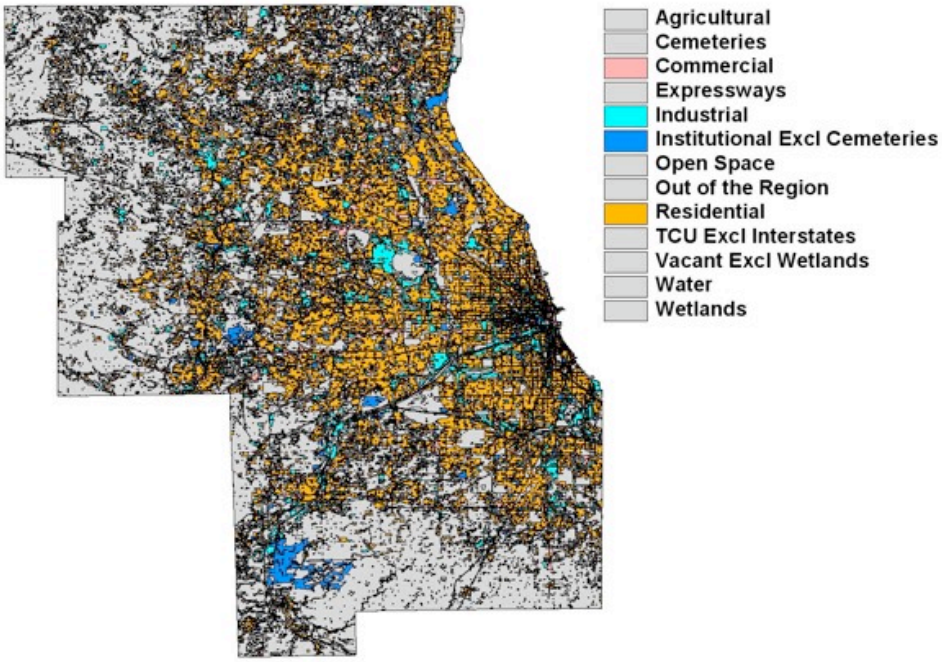

Figure A2.1 Land use for residential, commercial, and industrial zones within the Chicago metropolitan area.

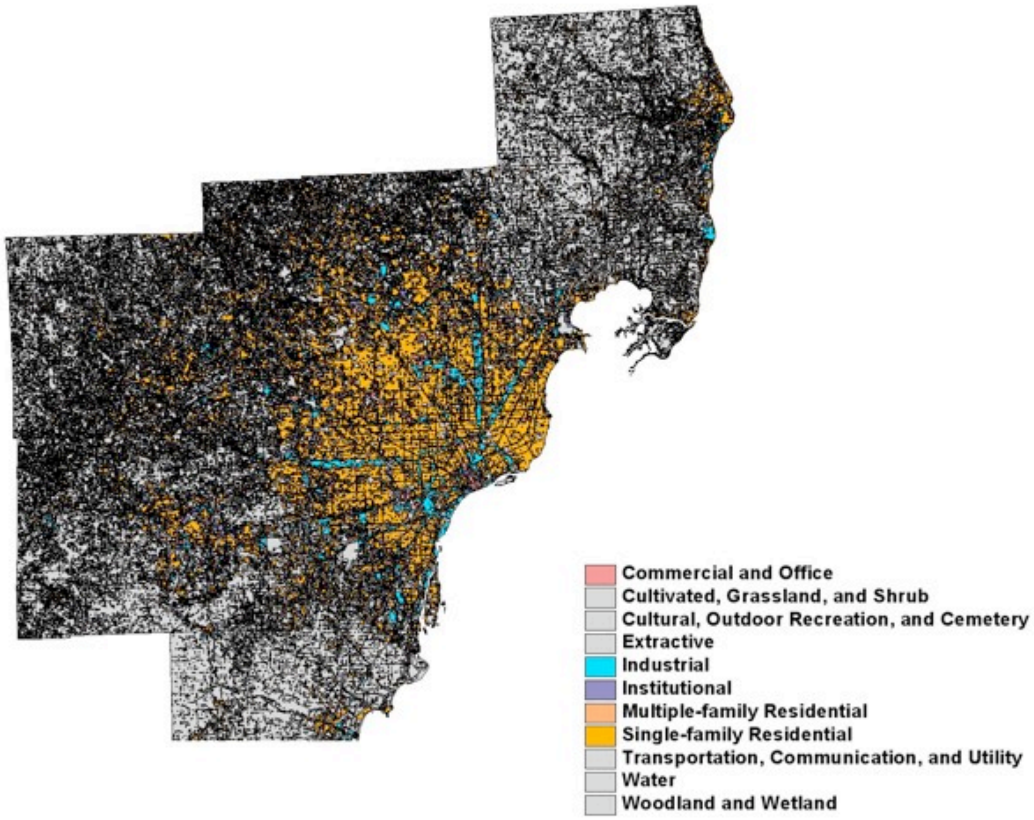

Figure A2.2 Landuse for residential, commercial, and industrial zones within the Detroit metropolitan area.

For the Detroit metropolitan area of 886,000 ha, it was estimated that roofs cover 54,200 ha. In the Chicago metropolitan areas (948,000 ha), 65,400 ha are estimated to be roofs. Environmental benefits for the metropolitan areas were then evaluated according to the procedures previously discussed at the building scale.

The main difference of evaluating stormwater benefits at the city scale relative to the building scale, is the impact on stormwater infrastructure. Deutsch et al (2005) estimated that greening ten percent of green roof ready buildings in Washington, DC (approximately 70 ha) would reduce infrastructure costs to the city's long-term control plan (LTCP) (estimated capital cost of 1.9 billion dollars) by 10 million dollars assuming the roofs would retain 450,000 cubic meters of the 97 million cubic meters of stormwater that are managed annually. For the Detroit metropolitan area, assuming a retention rate of 65% of annual precipitation (0.84m for Detroit), greening ten percent of rooftops (5420 ha) would retain more than 29 million cubic meters of water. Considering that the estimated costs of the LTCP are $3.5 billion (SEMCOG, 2001), this translates to a reduction of $ 114 million, suggesting substantial opportunity to invest in above-ground roof infrastructure.

The potential health benefits at the city scale from uptake of NO_X were determined and translated into economic terms according to the two EPA health valuation estimates used in Chapter 4. Greening ten percent of Chicago roofs (6540 ha) would uptake 17,400 Mg_{NO2}/y resulting in city-wide benefits of $29.2 million to $111 million annually. For Detroit, greening ten percent (5420 ha) would uptake 14,400 Mg_{NO2}/y, resulting in benefits of $24.2 million to $91.9 million annually.

Large-scale roof greening also indirectly benefits public health by reducing energy consumption. Green roofs can reduce peak energy demand resulting in fewer atmospheric emissions from power plants that run additional generators at peak times. Based upon emissions data for coal-fired utilities and natural gas combustion (Franklin & Associates, 1992), estimates for avoided emissions for greening ten percent of Chicago are 2.21 million Mg_{NO2}/y and for Detroit are 1.83 million Mg_{NO2}/y. Greening ten percent of metropolitan roofs would result in 1.53E4 to 1.85E4 Mg of NOx reduction (from direct and indirect uptake) reducing annual public health costs between $25.8 million to $97.7 million in Detroit and between $31 million to $118 million in Chicago.

These initial results indicate the substantial opportunities for green roof implementation at scale. This is increasingly recognized by municipal governments through large-scale studies (Toronto, Ontario; Washington, DC) and policies requiring greening (Tokyo, Japan; Seattle, Washington). Further analysis incorporating local environmental factors (e.g. neighborhood air quality) can assist planning efforts and regional policies to address environmental or public health impact ‘hot spots’ (e.g. poor air quality, urban heat island, storm sewer overflows) via mapping to focus greening efforts on neighborhoods that will receive the greatest benefit.

Appendix 3

Soil Media Design: Transport Mechanisms for Nitrogenous Fertilizers

SEDUM, which we hope will become an engineering design tool for assessing green roof efficiency, indicated that increasing the organic content of soil media, the depth of the soil media, and the density of the soil media are key design parameters involved in increasing reactive nitrogen species uptake. Preliminary studies have evaluated the impact of green roofs on the water quality running off the roof when a nitrogen-based fertilizer is applied.

At issue is the practice of implementing green roofs, and the extent that fertilizers should be applied to assist with plant establishment and survival. To assess advection and diffusion of fertilizer through a vegetated roof the following assumptions were made. First, as the soil matrix is often comprised of lightweight material that sustains plant growth while providing adequate draining, it was assumed that the green roof system would contain two layers, a peat layer to promote growth and a gravel layer to promote drainage. Soil survey data provided the requisite information on the peat and gravel layers (USDA, 2006; Reisenauer, 1963). Second, suggested lawn fertilizer and irrigation information were used to develop an application rate (Miracle Grow Garden Feeder). Figure A3.1 depicts the extensive roof system assumed for this analysis:

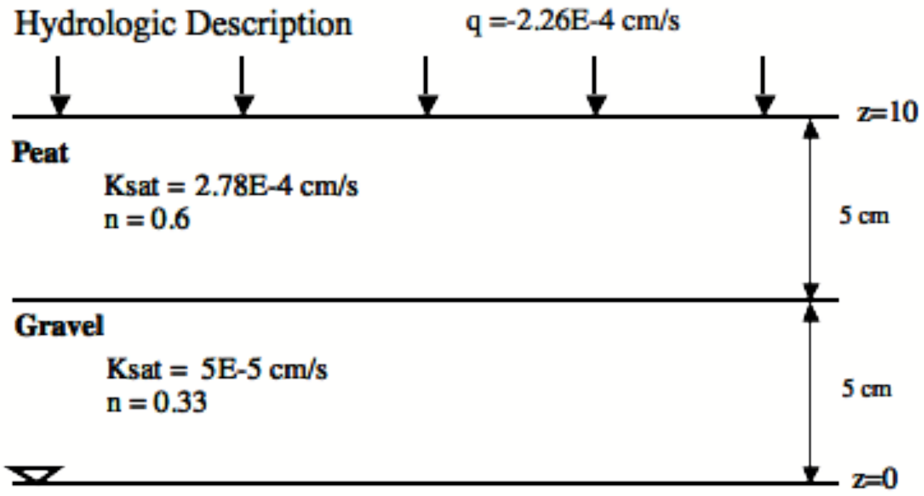

Figure A3.1: Hydrologic description of green roof system.

For this study, the upper layer is 5 cm of peat with the bottom gravel layer with a depth of 5cm. With this information and the soil survey data, soil moisture characteristics and soil moisture profiles were developed for both soils.

The information from these curves aided the development of an appropriate advection-dispersion equation for both soils. It is assumed that peat has a fractional organic content of 0.08 with gravel having no organic content. Therefore, sorption is only taken into account for the peat layer. As no biodegradation information for urea ($(NH_2)_2CO$) was available, it was assumed that sorption was the primary method for removal of urea. As a result, the following equations were used for effective diffusion and developed from Crank (1975):

Effective diffusion for gravel (no sorption),

$$D_E = \frac{K_H D_g^s + D_l^s}{\Theta + aK_H} \tag{A2.1}$$

Effective diffusion for peat (with sorption),

$$D_E = \frac{K_H D_g^s + D_l^s}{\rho_b K_d + \Theta + aK_H} \tag{A2.2}$$

where K_H is the Henry's constant, D_g^S is the diffusion coefficient of gas in soil, D_l^S is the diffusion coefficient of water in soil, Θ is the water content, a is volumetric air content, ρ_b is the soil bulk density, and is K_d is the distribution coefficient in a linear isotherm.

To obtain a concentration profile (C(x,t)) at the bottom of the gravel layer with no biodegradation and no sorption, the following equation was used:

$$C(x,t) = \frac{C_o}{2}\left\{ \operatorname{erfc}\frac{x - \left(\frac{q}{n}\right)t}{2\left[D_h t\right]^{1/2}} + \exp\left(\frac{qx}{nD_h}\right)\cdot \operatorname{erfc}\frac{x + \left(\frac{q}{n}\right)t}{2\left[D_h t\right]^{1/2}} \right\} \tag{A2.3}$$

To include sorption for the peat layer, the equation is modified slightly.

$$C(x,t) = \frac{C_o}{2}\left\{ \operatorname{erfc}\frac{R_d x - \left(\frac{q}{n}\right)t}{2\left[R_d D_h t\right]^{1/2}} + \exp\left(\frac{qx}{nD_h}\right)\cdot \operatorname{erfc}\frac{R_d x + \left(\frac{q}{n}\right)t}{2\left[R_d D_h t\right]^{1/2}} \right\} \tag{A2.4}$$

where x is the position (cm) at time t (s), C_O is the initial uniform concentration, q is the progression rate (cm/s), n is porosity, D_h is the hydrodynamic dispersion, and R_d is the retardation coefficient due to sorption. The concentration at the exit of the peat layer was assumed to be the inlet concentration for the gravel layer.

Based upon available soil data, soil moisture characteristics were developed and are shown in Figure A3.2.

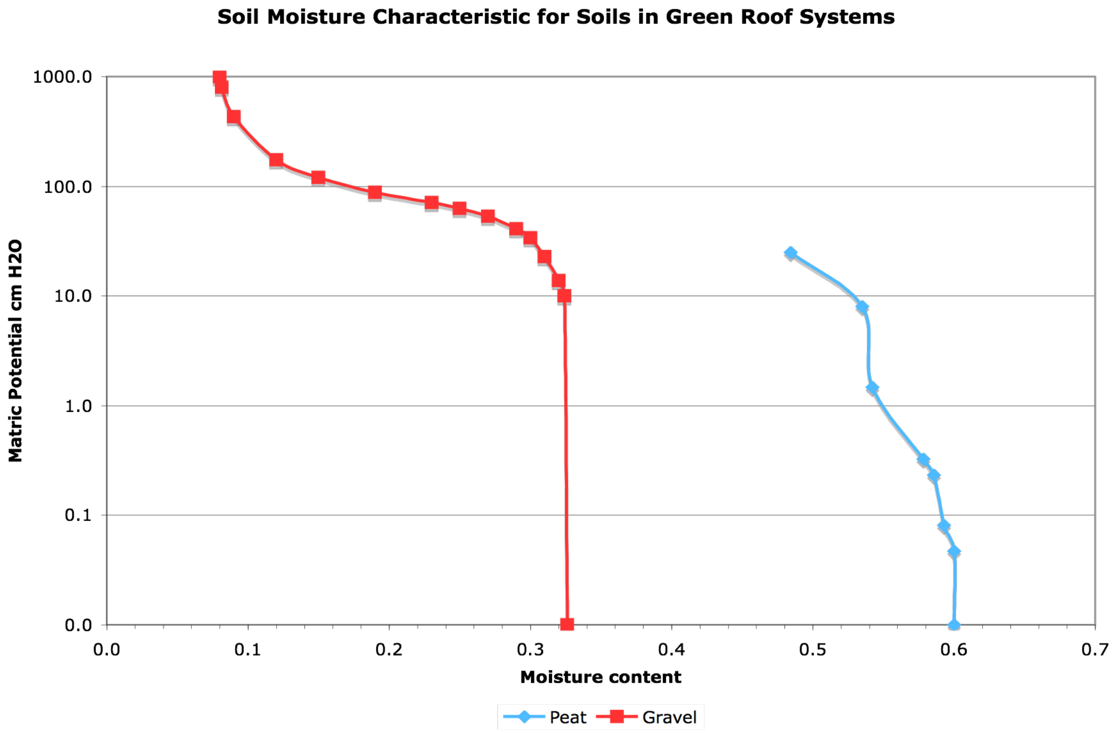

Figure A3.2: Soil moisture curves (SMCs) for green roof system.

Figure A3.2 shows that the soil layers permit proper drainage. Although the available data did not provide for a complete soil moisture curve for the peat, the moisture content is higher in the peat than in the gravel at a given matric potential. The gravel has lower residual moisture content than peat allowing for the roof to drain, and the higher moisture content in the peat should assist plant growth.

Assuming the irrigation flow rate of 2.24e-4 cm/s, the steady-state saturation profile for the green roof is shown in Figure A3.3.

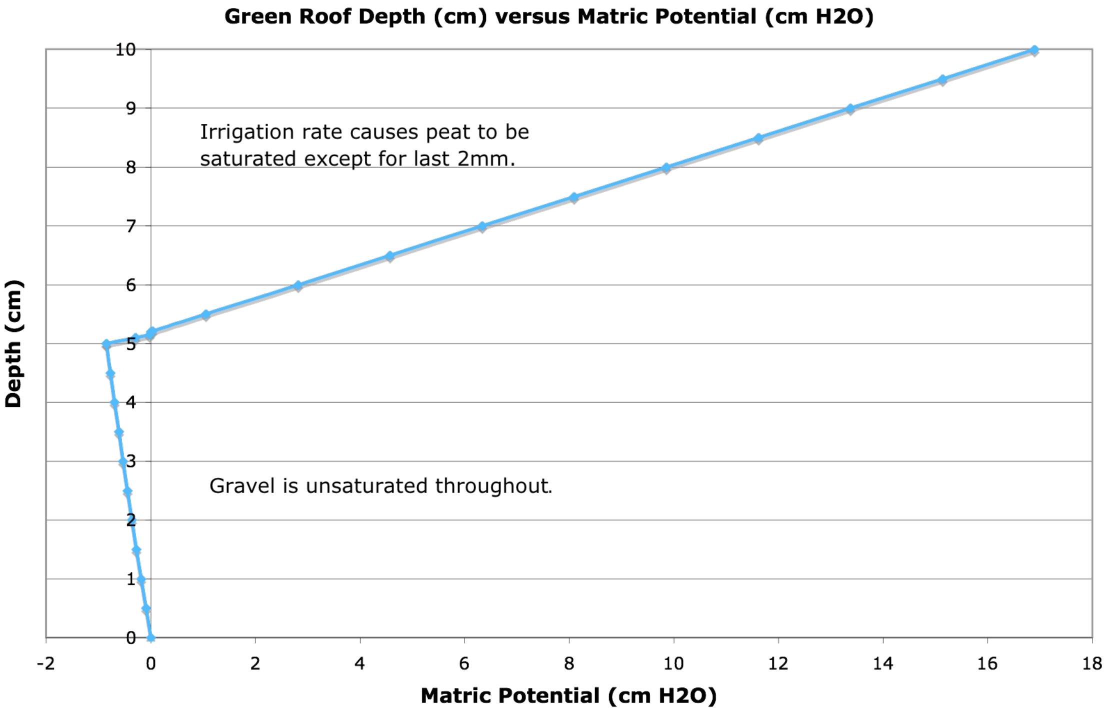

Figure A3.3: Saturation profile through the green roof system.

From the profile, one can see that the peat is completely saturated (with the exception of the last two millimeters). The saturation limits urea diffusion to the water phase. The gravel is unsaturated, so both gas and liquid diffusion must be considered.

The average moisture content was determined from the saturation profile and integrated into the advection-dispersion equation. While typical fertilizer application is applied at 2.24E-4 cm/s for 15 minutes for a lawn 74.4 m^2, the breakthrough curves for this analysis evaluated a continuous release of urea. This provides a maximum observable concentration at the conventional drain outlet, which would provide a conservative estimate for potential water quality impacts. Based upon these criteria, the breakthrough curves are presented.

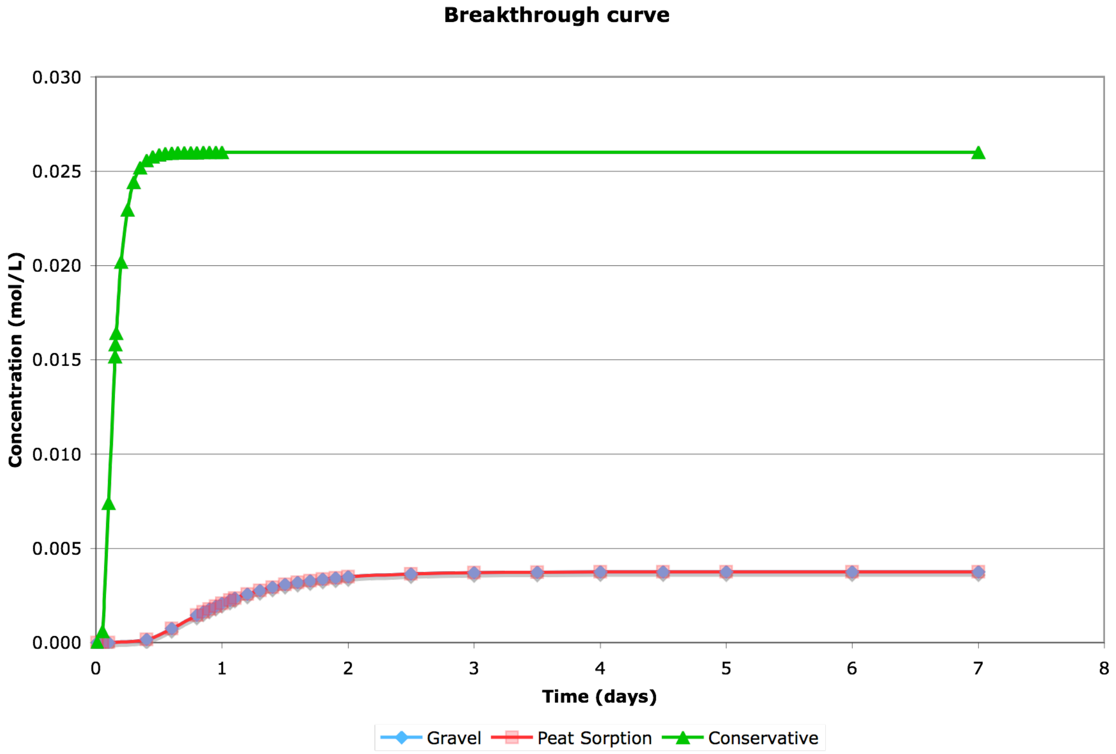

Figure A3.4: Breakthrough curves for urea at z=0, the bottom of the gravel layer.

As can be seen from Figure A3.4, the urea is readily sorbed to the organic fraction within the peat, reducing the available urea within the soil. The initial application concentration of 26mM reduced to 3.26mM at the bottom of the system. Fourteen percent of the urea applied to the green roof under conventional fertilizer application exits the roof through the drainage system. Due to the shallow depth of both soil layers and the assumption of no sorption within the gravel layer, no differences between the concentration exiting the peat and the concentration exiting the gravel layer were observed.

From this preliminary work, it appears that continued fertilizer application impacts water quality in runoff, unless peat (or other highly sorptive layers) are incorporated in the media design. Assuming a 10-cm bi-layer media of peat and gravel, preliminary results indicate that sorption due to the organic content in the peat layer effectively reduced the available concentration of urea-based fertilizer from 26 mM of urea at the surface to 3.36mM at the bottom of the gravel layer.

Further research is needed to evaluate the significance of this impact on stormwater runoff quality and receiving waters, when compared to other non-point sources of agricultural runoff. The inclusion of a soil with a high organic fraction such as peat reduced the concentration of urea in the effluent. The Ksat (saturated hydraulic conductivity) for the gravel suggested efficient transmission of water through the soil, which leads to no observed concentration differences between the solution exiting the peat and the solution exiting the gravel at the same time. Future investigations could evaluate the impact of a pulse application of urea or a time limited application (representing maintenance protocols for plant establishment). This first analysis provides a conservative estimate of the urea concentration in water runoff and suggests the need for future investigations in this area. Variations in soil media thickness could also affect the results and would need to be evaluated for broader conclusions on green roof systems. If green roofs are adapted at a large scale, recommendations for fertilizer application for vegetated rooftops may be needed to minimize negative water quality impacts. SEDUM can be used to quantitatively compare the roof design efficiency for urea retention at scale. Furthermore, future work can incorporate the cost of fertilizer implementation (as part of roof operations and maintenance) relative to the other costs and benefits of green roofs.

Appendix 4

Incorporation of Green Roofs into Tropospheric Models

While results from SEDUM indicated important design parameters for soil media and indications on climate conditions that favor uptake of air pollutants, it did not incorporate or provide information on temporal trends. Introduction of vegetation at larger scales can change the surface albedo, humidity, and introduces biogenic volatile organic compounds (BVOCs) within the community (Rosenzweig et al., 2006). These changes alter the rates and paths of atmospheric chemical reactions in a local airshed. While the potential for plants to uptake reactive nitrogen species has been shown, the fate of additional emissions to the atmosphere is less clear. Plants increase humidity through evapotranspiration, change surface albedo, and depending on the type of plant can emit biogenic VOCs. Emissions and albedo change affect tropospheric reaction rates for chemical species potentially affecting long-range transport of compounds and chemical lifetimes in the atmosphere. Further research into the effects of large-scale vegetation use in urban areas should include these complexities.

A preliminary study to investigate potential effects was conducted for New York City, NY. NYC was selected because of available data on potential urban heat island reduction effects from large-scale greening and the availability of climate and air quality data (Rosenzweig et al., 2006). These data indicated that, by increasing the amount of green surface area, temperature is expected to decrease, albedo should increase, actinic flux (the radiation flux within the atmosphere include direct and scattered forms) will increase, photolysis should increase, and humidity should increase (resulting in an increase of hydroxyl radicals). Scenarios were run to investigate what would occur under increased emission of isoprenes. Although sedum plants are not known to be isoprene emitters, many other plants are considered and implemented as a function of climatic region of roof implementation.

A photochemical simulation box model was run assuming a polluted region (city) with airflow inputs from a relatively clean environment (Sillman, 2006). Two scenarios were evaluated to represent an urban area with and without green roofs, with focus on exploring changes in temperatures, biogenic volatile organic compounds, and surface albedo. The model was used to evaluate the effects of decreased temperature, increased actinic flux, and potential increase in BVOCs. A residence time of three days was chosen to observe potential impacts of green roofs in a city with stagnant air. A small decrease was observed in ozone concentrations, with greater decreases observed in aldehydes, carbon monoxide, and formaldehyde as shown in Figure A4.1 -Figure A4.5.

Green roofs reduced ozone concentrations. The model did not include the additional benefit of uptake of nitrogen oxide species by vegetation as presented in Chapter 5. The incorporation of isoprene emissions affected the ozone concentration (as NO_X in combination with VOCs can elevate O_3). A greater reduction in ozone could be realized by selecting plants with high uptake potentials for NO_X and do not emit significant amounts of isoprene.

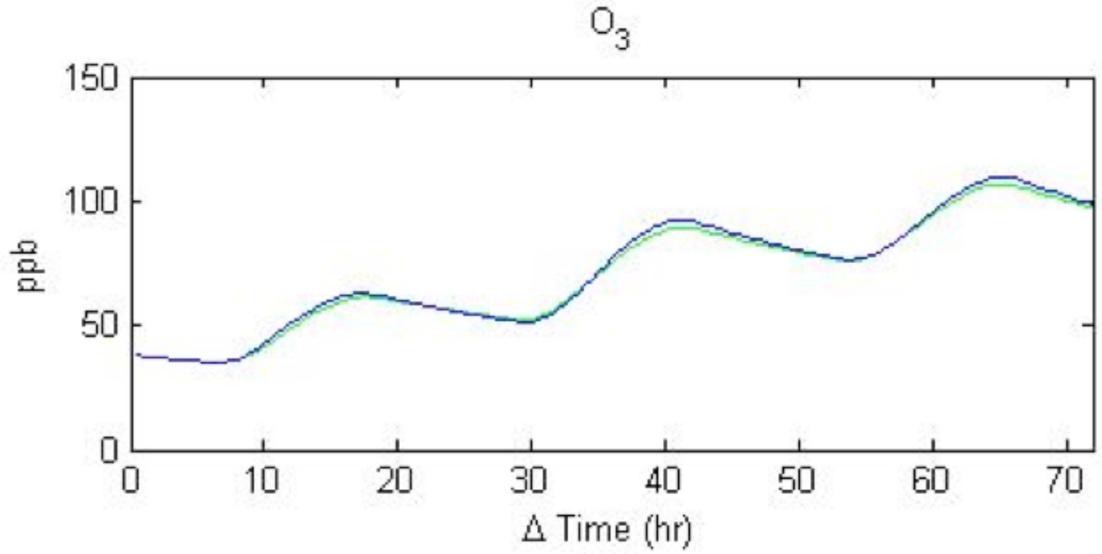

Figure A4.1 Estimated ozone concentration with green roofs (green) and without green roofs (blue).

A sensitivity analysis was conducted to explore the impact of temperature on the change in ozone concentration as the result of incorporating green roof vegetation (Figure A4.2). A greater temperature decrease resulted a larger decrease in ozone concentration.

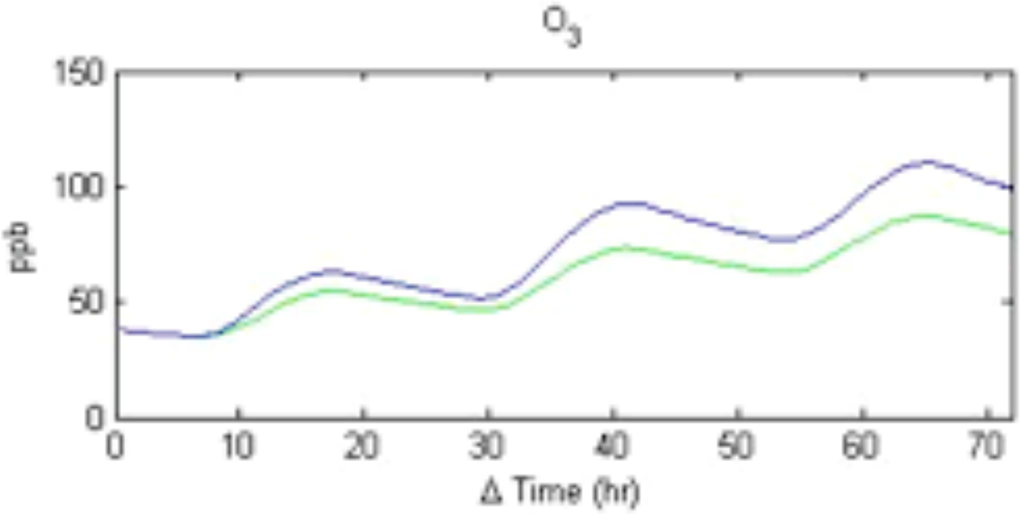

Figure A4.2 Estimated ozone concentration with no observed urban heat island effect with green roofs (green) and without green roofs (blue).

Increased photolysis rates resulted in elevated OH and NO concentrations resulting in faster reactions with VOCs, which decreased the concentrations of aldehydes, carbon monoxide, and formaldehyde as seen in Figure A4.3, Figure A4.4, and Figure A4.5.

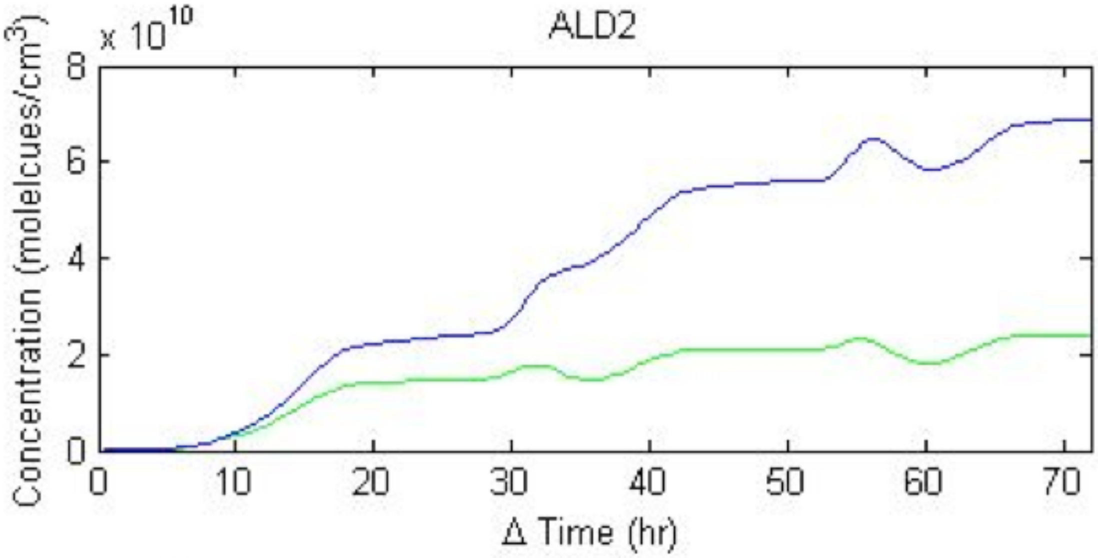

Figure A4.3 Estimated aldehyde concentration with green roofs (green) and without green roofs (blue).

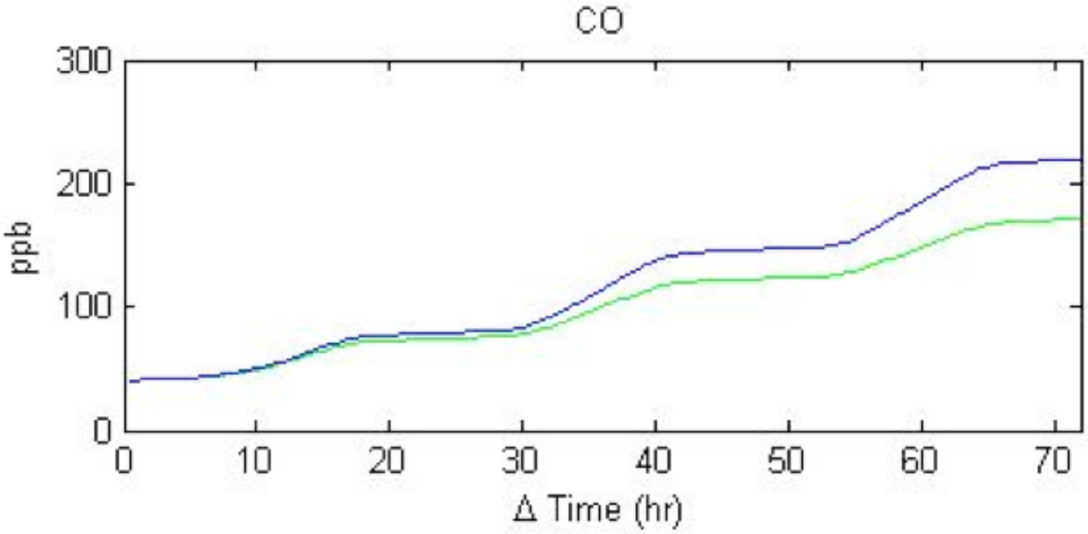

Figure A4.4 Estimated carbon monoxide concentration with green roofs (green) and without green roofs (blue).

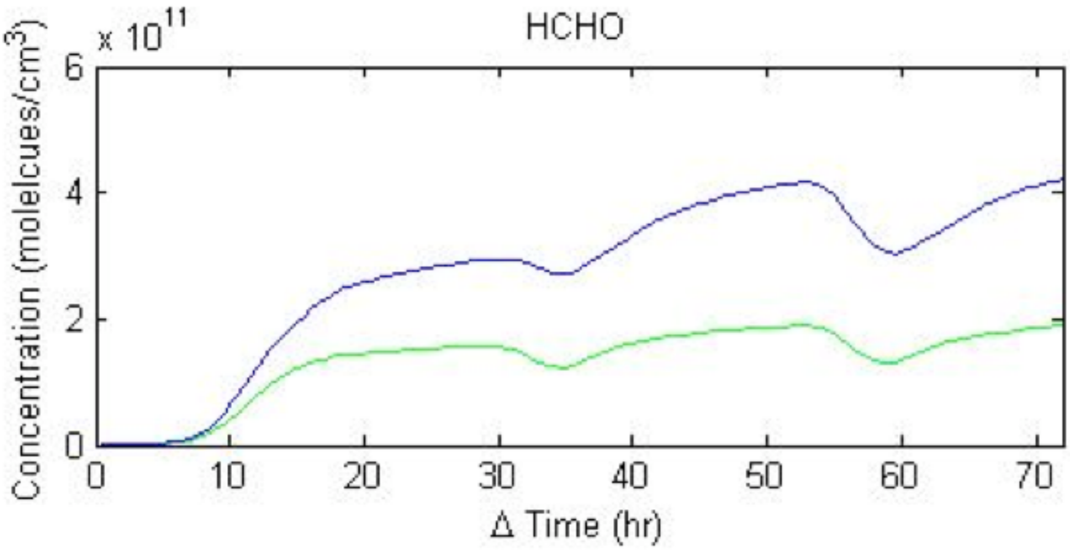

Figure A4.5 Estimated formaldehyde concentration with green roofs (green) and without green roofs (blue).

Herbaceous plants tend to have low emissions of VOCs; however, there are exceptions, and the rate of emission from sedum is unknown (Guenther, 2007). Further research is needed to assess the BVOC emission rate of green roofs as emissions can change when plants are stressed, which can occur on a rooftop environment. An emission profile for green roof plants would be useful to incorporate in SEDUM to evaluate the benefits of air pollutant uptake and thus health impacts. These initial investigations into the impact of green roofs on urban air chemistry indicates future research needs. For example, the box model bases humidity as a function of temperature. However, increasing the total surface area of vegetation in a city increases humidity through increased opportunity for evapotranspiration. Humidity increases the oxidizing power of the atmosphere and further alters photochemical reaction rates.

Translating the key research needs highlighted here (scalability, soil media design, and impact on tropospheric chemistry) into economic terms will inform designers in the optimization of green roof systems, and aid the public sector in developing appropriate policies for proper valuation to encourage this technology to address the multi-faceted environmental problems that impact urban areas.

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