EVALUATION OF GREEN INFRASTRUCTURE PRACTICES USING LIFE CYCLE ASSESSMENT

By

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DEDICATION

I dedicate this thesis to my grandfather

David Gross

ABSTRACT

This study uses life cycle assessment (LCA) to evaluate and compare the environmental, economic, and social performance of green infrastructure practices. The scope of this analysis is cradle to grave benefits and impacts of selected green infrastructure stormwater best management practices (BMPs). Fully functional and continuously monitored BMPs at the Villanova University campus were used in this study. These green infrastructure practices are representative of BMPs throughout the Philadelphia Area. Results are normalized using stormwater management regulatory guidelines. Metrics used to evaluate and compare green infrastructure practices include global warming potential, acidification potential, human health cancer impact, human health non-cancer impact, respiratory effects, eutrophication potential, ozone depletion potential, eco-toxicity, smog formation potential, labor impacts, and life cycle economic costs. Based upon the results of the study, recommendations are made to improve green infrastructure performance and to promote a holistic and interdisciplinary approach to the design and implementation of these practices. Using the methodology developed in this study, professionals of the future will be able to better implement sustainable and restorative development projects by designing and managing green infrastructure practices to achieve not only stormwater management goals but also broader environmental, economic, and social goals throughout the complete life cycle of a project.

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CHAPTER 1: INTRODUCTION

1.1 Infrastructure

For the first time in history, the majority of the world's population lives in urban areas (United Nations Population Fund, 2007). These urban residents expect the towns and cities they live in to provide them with many services including clean air, clean water, effective waste removal, a reliable energy supply, transportation, communication, and recreational opportunities (Wolf, 2003). Infrastructure is designed to provide these services on a community scale.

Infrastructure is defined as the substructure or underlying foundation, especially the basic installations and facilities on which the continuance and growth of a community depends (Merrian-Webster Online Dictionary, 2010). Historically, infrastructure is thought of as engineered networks of structures, concrete and conduits. Traditional infrastructure can be separated into two categories: gray infrastructure and social infrastructure. Gray infrastructure is made up of roads, sewers, and utility lines. Institutions such as schools, hospitals, and prisons are called social infrastructure (Benedict and McMahon, 2002). In this paper, the term "traditional infrastructure" is referring specifically to gray infrastructure.

In the past, communities looked solely to traditional infrastructure to provide services to their residents. This gray infrastructure typically requires a large initial investment of community resources to implement and a continued investment of community resources to maintain. Today, the development of green infrastructure is changing the way communities think about providing these services and making them sustainable in order to improve the quality of life of their current residents and for future generations of residents.

1.2 Green Infrastructure

Green Infrastructure is defined as “an interconnected network of waterways, wetlands, woodlands, wildlife habitats, and other natural areas: greenways, parks and other conservation lands; working farms, ranches and forests; and wilderness and other open spaces that support native species, maintain natural ecological processes, sustain air and water resources and contribute to the health and quality of life for communities and people” (Benedict and McMahon, 2002). The United States Environmental Protection Agency’s (EPA) definition includes engineered systems that mimic natural processes (Greening EPA Glossary, 2010). In this paper, the term “green infrastructure” encompasses both natural practices and engineered systems that maintain and restore ecological processes. This study specifically examines stormwater best management practices (BMPs), which are green infrastructure practices such as green roofs, rain gardens, and permeable pavements, designed primarily to provide stormwater management benefits. These decentralized stormwater BMPs can capture, infiltrate, and evapotranspirate rain where it falls, thus reducing, slowing, and cleaning stormwater runoff, recharging aquifers, and improving the health of downstream waterways (CNT & American Rivers, 2010). The terms “stormwater BMP” and “green infrastructure practice” are used interchangeably throughout this paper.

In the United States, the pace of land development far exceeds the rate of population growth. The problem is not growth itself but the pattern of growth. A history of haphazard development has resulted in the loss of many natural areas, the fragmentation of open spaces, the degradation of water resources, a decreased ability for nature to respond to change, the loss of many ecological goods and services, increased costs of public services, and higher taxes. These trends have helped to spark a movement towards green infrastructure. Societal changes that have influenced this shift include recognition of the problems with urban sprawl and landscape fragmentation, watershed management and combined sewer overflow plans, federal water quality mandates, endangered species protection and conservation plans, marketability and value of residential property near green spaces, community revitalization efforts, government smart growth policies, and the growing support for environmental sustainability. To achieve sustainable growth, development and redevelopment with both traditional and green infrastructure must be economically sound, environmentally friendly, supportive of community livability, and overall enhance quality of life (Benedict and McMahon, 2002).

When implemented in developed areas, green infrastructure can protect and restore naturally functioning systems and provide a framework for future sustainable development. The use of green infrastructure can be even more impactful when implemented at the planning stages of new development. It is much easier to preserve an existing natural habitat then to try to construct and recreate one. Therefore, the first principle of development with green infrastructure should be to determine where not to develop and what to preserve. It is ideal to strategically design a linked green infrastructure system that functions as a whole. An example is connecting parks with preserves, riparian areas, wetlands, and other green spaces. Another important aspect of implementing green infrastructure is that it is grounded in science. To achieve this, a multidisciplinary approach to green infrastructure is necessary. It should include but not be limited to the fields of civil engineering, conservation biology, landscape ecology, urban and regional planning, landscape architecture, and geography (Benedict and McMahon, 2002).

Green infrastructure provides benefits to people, ecosystems, and the economy beyond those of traditional infrastructure. Therefore, it is a key component for sustainable growth of communities and a critical public investment (Benedict and McMahon, 2002). Green infrastructure programs, such as the City of Philadelphia, Pennsylvania's "Green City, Clean Waters" program, are major steps toward a more sustainable urban model. More information on this Philadelphia green infrastructure program can be found on the Philadelphia Water Department's Office of Watersheds Website (Philadelphia Water Department, 2011).

1.3 Research motivation

The stormwater management benefits and performance of green infrastructure stormwater management practices have been well documented and continue to be studied and monitored. Interdisciplinary benefits of green infrastructure practices have also been identified. Benefits beyond stormwater management include recreation, community aesthetics, employment opportunities, energy savings, carbon footprint reduction, and air quality improvement. Although these benefits are recognized and accepted, minimal research exists to quantify these benefits and to relate their value to specific green infrastructure practices. Current research also seemingly struggles to indentify the external costs and impacts associated with the construction, maintenance, and decommissioning/replacement of green infrastructure practices. Green infrastructure is currently designed to manage downstream impacts of stormwater without consideration of “up-stream” impacts associated with the implementation and operation of these systems. This gap in knowledge incites to questions such as:

1) Do green infrastructure benefits outweigh these “up-stream” impacts?
2) What and where are the non-monetary costs and benefits throughout the life of a green infrastructure practice?
3) Are some green infrastructure practices “greener” than others?
4) What methods and tools can be used to quantitatively assess green infrastructure benefits and impacts?

1.4 Life cycle assessment

Life cycle assessment (LCA) is an environmental management tool that can be used to evaluate impacts of a product, process, service, or other complex system throughout all stages of its life cycle. LCA methodology traditionally considers all material and energy flows from “cradle to grave.” Depending on the goals and scope of the LCA, this may include but not be limited to extraction and provisions of raw materials, manufacturing, transportation, operation and maintenance activities, reuse or recycling, and finally disposal, decommissioning, or replacement (Curran, 2006). Studying complex systems, such as green infrastructure practices, through a life cycle lens allows for the estimation of cumulative impacts of human actions, including both long-term and indirect impacts (Kirk et al., 2006).

1.5 Research objectives

The goal of this study to use life cycle assessment as a tool to estimate cumulative impacts and benefits associated with the implementation of green infrastructure practices.

Selected green infrastructure practices are to be evaluated and compared both quantitatively and qualitatively across a wide range of impact categories. Additional goals of this research are as follows:

1) To establish a methodology for performing life cycle assessment studies specific to green infrastructure practices;
2) To evaluate the applicability and usefulness of existing tools and models as they apply to green infrastructure LCA;
3) To identify and assess significant impacts and the potential for improvement throughout the life cycle of green infrastructure practices;
4) To make recommendations that will promote a holistic and interdisciplinary approach to the design and implementation of green infrastructure.

This study is intended to aid professionals to better realize sustainable site and building design though the selection of appropriate green infrastructure practices to achieve not only stormwater management goals but also a wider range of sustainability objectives throughout the complete life cycle of a project. The results of the study are intended to be used in comparative assertions across green infrastructure practices and to be disclosed to the public.

CHAPTER 2: LITERATURE REVIEW

2.1 Stormwater management with green infrastructure

Stormwater management regulations and standards have continued to evolve since the establishment of the Clean Water Act in 1972. The goals of stormwater management for many years were focused solely on flood control. This goal was addressed through stormwater ordinances requiring reductions in peak flow rates by providing extended detention of stormwater with controlled release rates. These ordinances historically were and sometimes continue to be addressed through the implementation of centralized stormwater detention basins and other large detention structures.

With better understanding of the cumulative effects of human development, the goals of stormwater management have grown to include water quality, the recharge of aquifers, and geomorphology of our rivers. The implementation of the US EPA's National Pollution Elimination System (NPDES) Phase II regulations have applied these updated stormwater management goals to smaller catchments and development activities then every before (Kirk et al., 2006). These regulations have resulted in a shift in stormwater management strategy to include smaller scale, distributed stormwater management practices to address water quality, volume reduction, and groundwater recharge goals. The shift away from more traditional "end of pipe" management practices and toward green infrastructure has become wide spread not just for new development activities but also in the redevelopment of urban areas. Implementation of this strategy in older urban areas is gaining momentum as a means to reduce stormwater loads on combined sewer infrastructure and thus reducing the frequency of combined sewer overflow (CSO) events.

There are various approaches that can be taken to reduce and control combined sewer overflow in urban areas with combined sewer infrastructure. Gray infrastructure approaches have typically been employed to control CSO events. These methods usually consist of large-scale concrete collection and storage systems. Implementing storage systems for CSO involves excavating and building large diameter storage tunnels and pumping collected stormwater to wastewater treatment plants for treatment and discharge. Although traditional infrastructure solutions have been proven effective in reducing the frequency of CSO events, they do not provide the additional environmental, social and public health benefits of green infrastructure. Tradition infrastructure does not address the root causes of urban stream impairment, which are modified flow patterns and habitat degradation. These techniques are designed to reduce peak flows and remove loads of specific pollutants rather than restoring hydrologic processes and habitat (Raucher, 2009).

The City of Philadelphia and the Philadelphia Water Department (PWD) have established themselves as national leaders in policy supporting green infrastructure in the urban environment. As part of the City's "Green City, Clean Waters" program, PWD has made important changes in their water billing structure for commercial properties to promote and support the expansion of green infrastructure throughout the city. Between July 2010 and June 2014, the PWD will be phasing in parcel-based water charges and phasing out existing meter-based water charges. In addition to their water and sewer use, properties will be billed on the amount of stormwater runoff they generate, based on their impervious area. This new structure creates incentives and opportunities to implement green infrastructure practices on private properties though the City. These properties can lower their water bills through the implementation of green infrastructure. Opportunities for credits toward a lower bill include reducing impervious surfaces, planting trees near pavement, basins or ponds, rain gardens, created wetlands, swales, subsurface infiltration, planter boxes, rainwater harvesting and reuse, porous pavements, and green roofs (Watershed Information Center, 2010). Not only does this program address the issue of reducing CSO events, it is great way educate the public about the importance and multidisciplinary benefits of green infrastructure.

2.2 Benefits of green infrastructure

Green infrastructure practices can generate a more valuable array of environmental, economic, and social benefits than traditional infrastructure and traditional stormwater peak flow reduction practices. Some natural and engineered green infrastructure practices that can be employed in urban areas include tree planting, tree canopy over impervious surfaces, disconnection of impervious cover, bio-retention and infiltration systems, rain gardens, constructed wetlands, subsurface infiltration, swales, permeable pavements, green roofs, and rainwater harvesting (Raucher, 2009). If properly implemented, these green infrastructure practices can provide stormwater management benefits that include the restoration of a more natural balance between stormwater runoff and infiltration, reduced flooding, water quality and aquatic ecosystem improvement, wetland creation and enhancement, control peak of runoff rates, reduced stream bank erosion, and the restoration and enhancement natural ecosystems (CNT and American Rivers, 2010). The following sections describe some of the benefits beyond stormwater management associated the implementation of green infrastructure practices in urban areas.

2.2.1 Recreation

Green infrastructure can create new locations for recreational activities and improve the recreational value of existing locations. This includes both creek side recreational opportunities from stream restoration and riparian buffer improvements, and non-creek side recreational opportunities from increased vegetated and treed acreage in urban areas. Long term improvements in downstream water quality can also result in increases of in-stream activities recreational activities such as boating and fishing (Raucher, 2009).

2.2.2 Community aesthetics

Green infrastructure, especially vegetated systems, improves urban aesthetics and community livability. The experience of nature in cities is integral to human health, well-being and quality of life (Wolf, 2003). Reduction of impervious areas, increases in vegetation, and some permeable pavements help to reduce sound transmission which can reduce local noise pollution. Increased pervious areas and vegetation, especially native vegetation, promote wildlife habitat (CNT and American Rivers, 2010). Several empirical studies show property values are higher when trees and other vegetation are present in urban neighborhoods (Raucher, 2009).

2.2.3 Heat stress reduction

Trees, green roofs, rain gardens, and other vegetated systems all create a cooling effect in urban environments. These green infrastructure practices create shade, reduce the amount of heat absorbing materials, emit water vapor, and cool hot air. Air temperatures can also be lowered by permeable pavements which absorb less heat then conventional pavements. While reducing the urban heat island effect, this cooling can reduce heat stress related illnesses and fatalities during extreme heat wave events (CNT and

American Rivers, 2010). Studies have shown that increasing vegetation by 10% in the City of Philadelphia could potentially reduce urban temperatures by between 0.4 and 0.7 degrees Fahrenheit (Raucher, 2009).

2.2.4 Employment opportunities

A major social benefit from the implementation of green infrastructure is the creation of “green jobs.” Jobs associated with traditional infrastructure or large civil works projects are not typically counted within an economically sound benefit-cost analysis because labor used in these projects would most likely be gainfully employed in other ventures. This is because specialized labor is need for the construction of conventional CSO systems such as plant expansion and boring and tunneling. Although these public works projects can stimulate an economy, traditional infrastructure options do not represent a real net gain in jobs.

The implementation of green infrastructure does create an opportunity to hire unskilled and potentially unemployed labors for landscaping and restoration activities. These “green jobs” can potentially have important social impacts by providing opportunities for the unemployed and impoverished. This could in turn provide further economic benefits to the general public through avoided costs of social services (Raucher, 2009).

2.2.5 Energy savings and carbon footprint reduction

As discussed in previous sections, green infrastructure can lower ambient temperatures. Trees and other vegetation also help shade and insulate buildings, block winter winds, and create an evaporative cooling effect. Green infrastructure practices can decrease large temperature swings of buildings, thus decreasing energy used for heating and cooling. Green roofs for example provide insulation and shade which reducing heating and cooling needs. Research has shown that green roofs in Philadelphia can generate annual savings of 0.39 kWh per square foot of roof for cooling, and savings of 123 MM BTUs per square foot of natural gas per building for heating (Raucher, 2009).

Green Infrastructure works to reduce the overall carbon footprint of a community. Energy savings from the reduced heating and cooling of buildings reduces CO_2 emissions, other greenhouse gas (GHG) emissions, and pollutant emissions at power plants. In combined sewer areas, removing stormwater with green infrastructure through infiltration and evapotranspiration diverts water from wastewater collection and reduces energy needed to pump and treat stormwater, which will decrease CO_2 emissions at power plants. Rainwater harvesting can reduce potable water use and thus reduce energy use associated with treatment and transport. Carbon footprint is also reduced though carbon storage and sequestration by vegetated green infrastructure practices (CNT and American Rivers, 2010).

2.2.6 Air quality improvement

Vegetation as a part of green infrastructure practices has the ability to improve urban air quality. Urban areas such as Philadelphia are classified by the EPA as exceeding the current National Ambient Air Quality Standards (NAAQS) for both ozone (O_3) and $PM_{2.5}$ (particulate matter down to 2.5 micrometers in diameter). Plant respiration from vegetated green infrastructure practices acts locally to remove air pollutants such as particulate matter, ozone, CO, SO_2, and NO_x. On a larger scale, reduction of heat island effect slows the reaction rates of nitrogen oxides and volatile organic compounds (CNT and American Rivers, 2010). As described in the previous section of this chapter, carbon sequestration decreases atmospheric CO_2 and reduced energy consumption decreases emissions of CO_2, SO_2, NO_x, and other air pollutants. Improved air quality benefits human health through reduction of incidence and severity of respiratory illnesses and cardiovascular conditions (Raucher, 2009).

2.2.7 Education opportunities

Green infrastructure increases awareness and understanding of the need for proper management of water resources. The aesthetic appeal of green infrastructure practice can be a spark for community interest. There are also opportunities for education and outreach programs that may include activities such as tree planting, landscaping activities, construction of neighborhood rain gardens, and rainwater harvesting projects. Unlike traditional most infrastructure projects, green infrastructure may promote community participation, cohesion, and pride (CNT and American Rivers, 2010).

2.3 Adverse impacts of green infrastructure

As with traditional infrastructure or any other construction project, the implementation, operation and maintenance, and decommissioning/replacement of green infrastructure practices will have environmental, social, and economic impacts. The majority of green infrastructure research is focused on stormwater management performance and overall benefits. This research has recently expanded to include life cycle cost and design optimization based on cost and stormwater management performance. With the current focus primarily on the added benefit of green infrastructure, impacts are seemingly being overlooked (Kirk et al., 2006). Green infrastructure implementation can involve environmental emissions for activities such as the extraction of raw materials, production and transportation of construction materials, excavation and other onsite construction activities, vehicle fuel during installation and maintenance, fuel for machinery and heavy duty vehicles, fertilizer to establish vegetation in some practices, and water to establish vegetation in dry periods. These releases to the environment can have long term impacts in the form of ozone depletion, global warming, smog formation, acidification, eutrophication, human health impacts, eco-toxicity, fossil fuel depletion, land use, and water use (Bare et al., 2003). The use of environmental management tools and methodologies, such as life cycle assessment, are necessary to understand the direct and indirect impacts of providing stormwater management as well as other benefits associated with green infrastructure.

2.4 Life cycle assessment background

Life cycle assessment is an environmental management methodology and tool that can evaluate and quantify environmental impacts of complex systems. A growing worldwide emphasis on sustainable development has lead to businesses, governments, and even individuals searching for opportunities to reduce natural resource consumption, improve energy efficiency, and minimize waste. LCA has become an effective decision support tool that helps to recognize evaluate these opportunities (Curran, 2006). As a decision support tool, LCA has been used with success by manufacturers of commercial products. In 1969, the Coca Cola Company embarked on the first product LCA study, by examining and comparing resource use and environmental releases of different beverage containers (Jensen, 1997).

LCA methodology and application had been slow to develop over the last four decades. In 1991, the use of LCA results to promote products was even denounced in a statement issued by eleven US State Attorney Generals. This statement expressed the need for a standard method of LCA to prevent broad marketing claims and deceptive advertising stemming from variable LCA studies (Curran, 2006). These concerns were eventually addressed by the International Standards Organization (ISO) 14000 series environmental management standards. In 1998, the release of ISO 14040 established standard principles and framework for LCA. Then in 2006, the release of ISO 14044 defined in detail requirements and guidelines for undertaking an ISO compliant life cycle assessment (ISO 2006b).

The development of internationally excepted standards of practice for LCA has helped more and more businesses to identify significant impacts in their supply chains, material selection, manufacturing processes, water management, and waste management. Many companies have found strategic and economic value through improved environmental performance of their products and supply chains. While the study of commercial products using life cycle assessment methodology has been ongoing since the late 1960s, the application of LCA to complex systems such as traditional and green infrastructure is a relatively immature area of study.

2.5 Green infrastructure LCA

As the number of life cycle assessment studies focused on traditional infrastructure practices is limited, LCA studies focused on green infrastructure practices are practically unexplored. Few studies in this area do exist, such as a study by Kosareo and Ries (2006) that uses LCA to examine green roofs. This study compares life cycle cost and environmental impact of intensive green roofs, extensive green roofs, and conventional roofs in Pittsburgh, Pennsylvania. A newly constructed extensive green roof and conventional roof were analyzed and monitored for this study, and a theoretical roof was analyzed to represent the intensive green roof. The database and process flow modeling software SimaPro 5.0, by PRé Consultants, was utilized by these researchers. Environmental impacts were evaluated using the following impact categories: ozone layer depletion, acidification, eutrophication, and global warming. A weighted environmental impact was also assessed using the Impact 2002+ weighting method. This weighting method produces a single dimensionless, weighted impact score for comparative purposes. Impact categories assessed to develop the Impact 2002+ score include: carcinogens, non-carcinogens, respiratory inorganics, respiratory organics, global warming potential, radiation, ozone depletion potential, ecotoxicity, terrestrial acidification, resource depletion (energy), and resources depletion (minerals). The results of this comparative study conclude that green roofs are a preferable option to a conventional roof because of a reduced environmental impact over the life cycle of a roof. This reduced environmental impact is attributed to the building energy benefits of green roofs and the increased life the roofing membrane below a green roof (Kosareo and Ries, 2006). It should be noted that the conclusions of this study are based on a large amount of assumptions including the climate conditions of Pittsburgh, PA and the comparison of a hypothetical intensive green roof to two real roofs.

Researchers Kirk et al. (2006) conducted a study life cycle assessment study examining multiple stormwater BMPs including bioretention practices, which fall under the definition of green infrastructure. This study is a comparative LCA of the following BMPs: an ADS water quality treatment device, a wet retention pond, a bioretention practice, and a gravel wetland. The goal of the study is to compare total environmental, human health, and economic impacts of hypothetical BMPs designed to manage a hypothetical one acre parking lot. These BMP designs were based on New York State stormwater design criteria for equivalent stormwater management performance. An assumption of a 30 year operational life was used for all BMPs. The scope of this LCA is cradle to gate. This scope includes design and construction of BMPs but excludes operation, maintenance, and decommissioning. Environmental impacts were assessed using the US EPA's National Risk Management Research Laboratory's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI). TRACI impact categories used in the study include global warming, smog formation, acidification, eutrophication, human health cancer, human health non-cancer, human health criteria air pollutants, eco-toxicity, and fossil fuel depletion. Environmental impacts were also normalized for comparison using the weighting values assigned by the US EPA Science Advisory Board. The study findings show that the weighting is necessary to compare BMPs because of variation in magnitude of impact across impact categories, but even with weighting the results are too similar to determine with any degree of certainty the BMP with the best environmental performance. Kirk et al. (2006) conclude that a complete BMP life cycle from cradle to grave needs to be evaluated to fully understand impacts and make more insightful comparisons between BMPs (Kirk et al., 2006).

CHAPTER 3: METHODOLOGY

3.1 ISO Environmental Management Standards

The methodology used in this study follows methodology set forth for life cycle assessment (LCA) by the International Standards Organization (ISO) under the ISO 14000 environmental management standards. ISO 14040 establishes standard principles and framework for life cycle assessment and ISO 14044 defines requirements and guidelines for undertaking an ISO compliant life cycle assessment. These standards outline a LCA framework which is comprised of four phases. The four phases of a LCA study include: the goal and scope definition phase, the life cycle inventory (LCI) analysis phase, the life cycle impact assessment (LCIA) phase, and the life cycle interpretation phase. *Figure 1* illustrates the complete framework and phases of a LCA as per ISO 14040. The following sections describe these phases as they apply to this green infrastructure study.

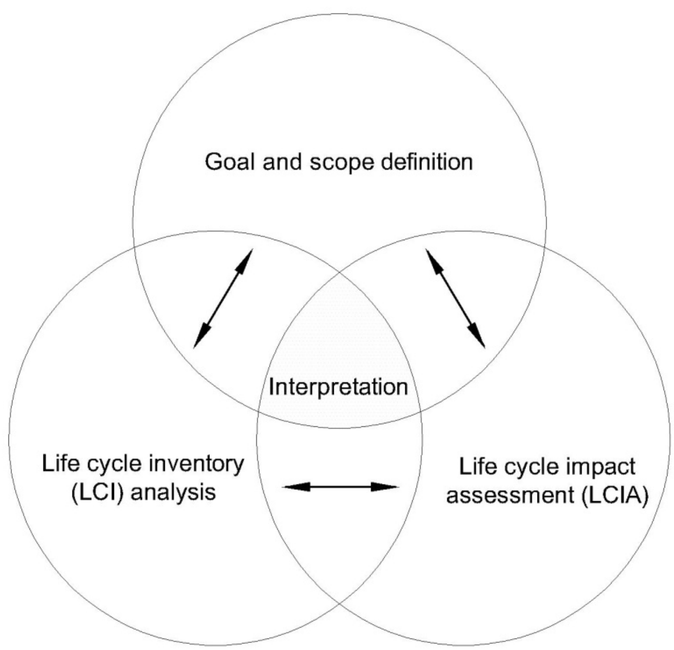

Figure 1. Life cycle assessment framework

3.2 Goal and scope definition

The goal of this study is to quantitatively and qualitatively assess and compare the benefits and impacts of selected green infrastructure practices. This study is intended to aid professionals to better realize sustainable site and building design though the selection of appropriate green infrastructure practices to achieve not only stormwater management goals but also a wider range of sustainability objectives throughout the complete life cycle of a project. The results of the study are intended to be used in comparative assertions across green infrastructure practices and to be disclosed to the public.

The scope of this study is cradle to grave benefits and impacts of selected green infrastructure practices. This includes every aspect of the practice life cycle from raw material production and transportation, to construction, to operation and maintenance, to end of life and decommissioning. Environmental, economic, and social impacts and benefits are to be assessed quantitatively where possible. Fully functional and continuously monitored BMPs at the Villanova University campus were used in this study. Practices selected for analysis include a rain garden, a green roof, and a pervious pavement site. These green infrastructure practices are assumed to representative of retrofitted BMPs throughout the Philadelphia Area.

The functional unit used in this LCA is *Impervious Drainage Area*. Drainage area was chosen as the functional unit in order to make direct comparisons between practices. Comparisons are made on a regulatory basis based on sizing guidelines detailed in the *Pennsylvania Stormwater Best Management Practice Manual* (*PA BMP Manual*) (PADEP, 2006). For example, to compare a green roof to a rain garden, the green roof would typically be sized at a 1:1 impervious drainage area to BMP ratio while the rain garden would generally be sized at a recommended 5:1 impervious drainage area to BMP infiltration area ratio as per *PA BMP Manual* guidelines. Using this method of normalization allows for a direct comparison of practices as they would be implemented for stormwater volume reduction.

3.3 Life cycle inventory analysis

Life cycle inventory (LCI) analysis consists of the identification and quantification of all relative inputs and outputs throughout the life cycle of a green infrastructure practice. In order to preserve recordkeeping and data quality, BMP life cycles were broken down into phases for data collection. This breakdown begins with the construction phase which in addition to onsite BMP construction activities includes inputs and outputs from the extraction, production, and transportation of raw materials. Next is the operation phase which consists of all inputs, outputs, and benefits accrued over the operational life of the green infrastructure practice. Finally is the decommission phase of the practice. This last phase is inclusive of any deconstruction, refurbishment, material disposal, or material recycling that may occur at the end of life of a green infrastructure practice. Various data collection methods and assumptions were used for each life cycle phase and are described in detail in the following chapters of this paper.

Presently (2011) operational BMPs at the Villanova University campus were used in this study. For the construction phase LCI, green infrastructure practice data is collected from engineering plans, contractor invoices, onsite inspections, interviews with professionals involved in the design and construction, and the analysis of photographic records. Inventories are taken of construction materials, transportation of materials, construction equipment operation, and onsite labor.

Operation phase LCI is made up of inputs and outputs that occur over the operational life of the practice. For example, this may include maintenance such as suction truck cleaning for pervious pavements or seasonal landscaping of vegetated practices. Outputs to be considered which are specific to vegetated practices are carbon sequestration and air quality improvement benefits. In order to gather vegetation data to assess these operational benefits, planting plants and detailed onsite vegetation surveys are to be utilized. Other sources of data gathering include maintenance records and interviews with maintenance personnel.

Limited information and research is available on the decommissioning of green infrastructure practices. Since none of the Villanova University BMPs have undergone decommissioning, LCI for this phase is based on assumptions supported by literature review. Throughout the complete LCI process, data gathered from these existing BMPs is used whenever it is possible and feasible. Assumptions based on literature review and information from specialized databases was utilized when necessary. Inputs and outputs from all phases are checked by mass and energy balances to complete the inventory analyses. *Figure 2* illustrates the general organizational structure used in this study for the life cycle assessment of a green infrastructure practice.

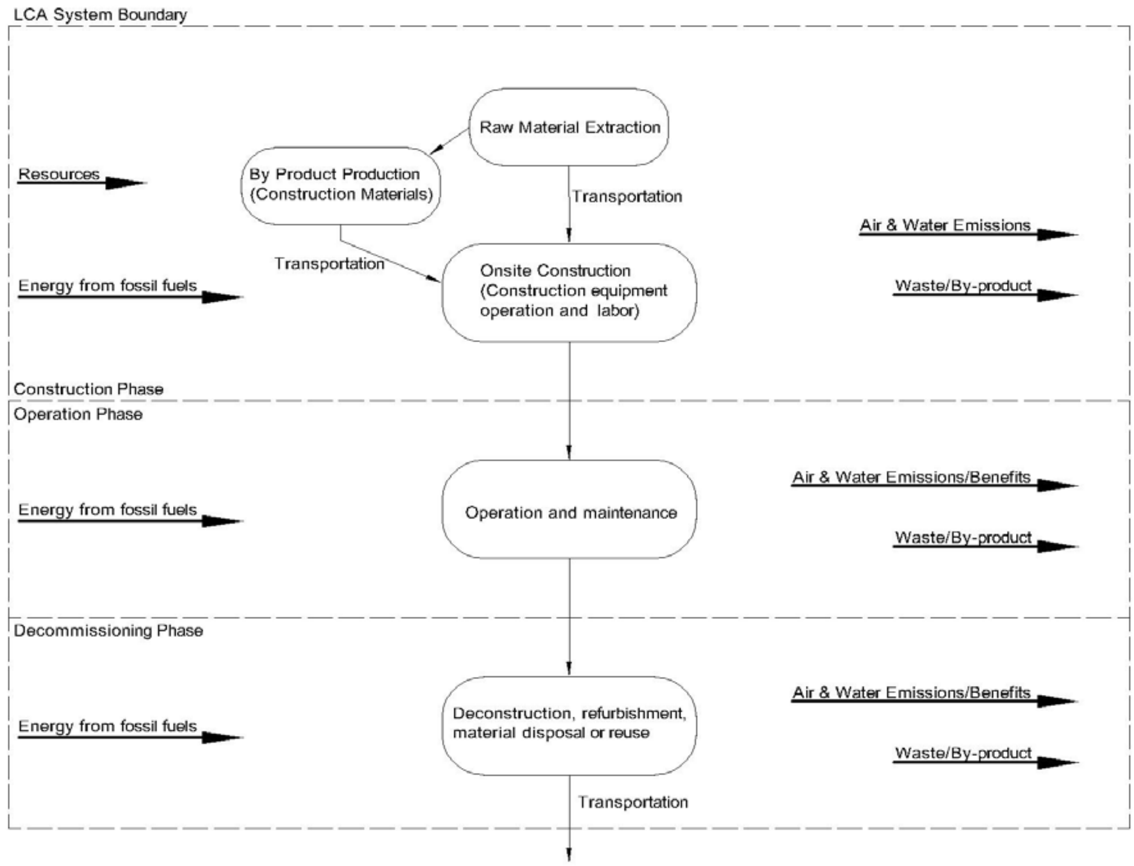

Figure 2. General organizational structure for LCA of a green infrastructure practice

3.4 Green infrastructure life cycle inventory tools

Existing databases, software, and models were utilized to assemble life cycle inventories for green infrastructure practices. These tools and their application in this study are described in the following sections of this paper.

3.4.1 United States Life Cycle Inventory Database

The U.S. Life Cycle Inventory (LCI) Database was developed by the National Renewable Energy Laboratory (NREL) to provide national standards for environmental LCA projects and to support the use of LCA as an environmental decision-making tool. This database contains comprehensive energy and material flows into and out of the environment for a wide range of materials, components, assemblies, and processes. The U.S. LCI Database contains high-quality U.S.-based LCI data (National Renewable Energy Laboratory, 2009). This data was applied wherever possible throughout this study.

3.4.2 SimaPro 7.2

SimaPro 7.2 is a process flow modeling program, by PRé Consultants, designed to assist users with ISO compliant LCA. This software tool is used to inventory and model the construction and decommissioning phases for green infrastructure practices examined in this study. Using the software, specific process flow models are created for the construction phase of each green infrastructure practice. The software is also used to model operation phase maintenance activities and operational benefits of practices when appropriate. In addition to the ability to create process flow models, this software contains comprehensive LCI databases. These built-in databases include data from the U.S. LCI Database, the Ecoinvent database, and the European Life Cycle Database (ELCD). Because of the limited LCA data available related to green infrastructure practices, modeling BMPs requires a variety of assumptions in order to make use of established and approved life cycle inventory databases. SimaPro 7.2 is also used as a tool for the accounting of energy and materials flows, the calculation of inventory results, and to define and examine impact categories (PRé Consultants, 2010).

3.4.3 i-Tree Eco

i-Tree Eco is the latest adaptation of the United States Department of Agriculture (USDA) Forest Service’s Urban Forest Effects (UFORE) model. The model uses collected vegetation data along with local air pollution and meteorological data to calculate the environmental effects and values of urban forests. Although typically this model has been used on a larger scale to assess the urban forest effects of a city, town, or community, the model also is able to model urban forest effects on a smaller scale, even down to a single tree. For this study, i-Tree Eco is used to examine and calculate environmental effects and values for individual vegetated green infrastructure practices. These benefits are applied over the operational phase of the LCI for vegetated practices. Data collection methods for model inputs include detailed field surveys and BMP planning plans. Air pollution and metrological data for locations throughout the United States are available within the model (US Forest Service, 2010).

3.5 Life cycle impact assessment

In the life cycle impact assessment (LCIA) phase, evaluations are made of the significance of potential impacts using the LCI results. Evaluations are relative and based on the defined functional unit of the study. As described previously, the functional unit used in this LCA study is *Impervious Drainage Area*. In order to normalize and make comparisons between practices, all impact categories are evaluated on a basis of impact per acre of impervious drainage area (impact unit per acre impervious DA). Significant impact pathways of individual green infrastructure practices are also identified in the LCIA phase.

The major impact categories examined in this study are taken from the U.S. EPA's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI). These impact categories include ozone depletion, global warming, smog formation, acidification, eutrophication, human health cancer, human health non-cancer, human health criteria pollutants, eco-toxicity, and fossil fuel depletion. The SimaPro 7.2

software contains built in routines to calculate and compile these TRACI impact categories (Bare et al., 2003). Social and economic impact categories are to be examined as well. These categories include labor impacts and life cycle economic costs of green infrastructure practices.

3.6 Life cycle interpretation

The life cycle interpretation phase of a LCA study examines and draws conclusions based on the results of the LCI and LCIA phases of the study. This phase involves the analysis of significant impact pathways and potential for improvement throughout the life cycle of a green infrastructure practice, an evaluation of assumptions used throughout the study, and a sensitivity analysis of life cycle inventory inputs. Also evaluated are the applicability, usefulness, and limitations of the identified LCI tools as they apply to green infrastructure LCA.

Based on the comparisons and evaluations of BMP life cycles, recommendations are to be made to promote a holistic and interdisciplinary approach to the design and implementation of green infrastructure. Results of this study are to be made available to the public as a reference for professionals to aid in the selection of appropriate green infrastructure practices to achieve not only stormwater management goals but also goals in other impact areas throughout the complete life cycle of a project.

CHAPTER 4: RAIN GARDEN LIFE CYCLE ASSESSMENT

4.1 Villanova University bio-retention rain garden

The rain garden selected in this study for life cycle assessment is the Villanova University bio-retention rain garden. This rain garden was constructed in August 2001, as a retrofit to an existing parking lot traffic island. The rain garden is located on the Villanova University campus in southeastern Pennsylvania, within the Darby-Cobbs Watershed. Stormwater runoff from a 1.2 acre drainage area is received by the rain garden. This catchment area is approximately 52% impervious and contains a roadway, parking areas, and a basketball court. The bio-retention rain garden has an approximate footprint of 0.1 acres and was originally designed to retain one inch of precipitation volume from its contributing drainage area (Ermilio, 2005).

Data gathering techniques for life cycle assessment of the bio-retention rain garden include engineering plans, contractor invoices, onsite inspections and survey, interviews with professionals involved in the design and construction, published literature, and the analysis of photographic records. As described in Section 3.3 of this paper, BMP life cycles were broken down into phases for data collection. These life cycle phases include a construction phase, an operation phase, and a decommissioning phase. This inventory represents the first step in completing the LCI phase for the rain garden. The described green infrastructure LCI tools used to be used to quantify all inputs and outputs related to each inventoried item. This is an iterative procedure that involves process flow modeling and a series of research backed assumptions.

4.2 Rain garden construction phase

Bio-retention rain garden construction took place between August 2 and August 25, 2001 (N. Abbonizio Contractors, Inc., 2001). This green infrastructure practice was designed as a research site by Dr. Robert Traver of Villanova University's Department of Civil and Environmental Engineering and was partially funded by the Pennsylvania Department of Environmental Protection (PADEP) 319 Non Point Source Monitoring Program. Construction was carried out by a local general contractor. Planting and the establishment of vegetation was accomplished by the Villanova University Facilities Department (Machusick, 2009).

As a research site, the bio-retention rain garden was equipped with flow monitoring and water quality sampling equipment. The manufacturing and installation of this monitoring and sampling equipment was deemed out of the scope of the study and is purposefully excluded from this life cycle assessment. This equipment is not essential to the implementation and function of a rain garden and inclusion in the study would not be representative of a green infrastructure practice outside of a research setting.

To inventory the material and energy flows for the construction life cycle phase of the bio-retention rain garden, data was collected primarily using the construction plans, the general contractor invoice, the nursery invoice, and analysis of photographic records. The general construction phase sequencing derived from this data is listed in the following section, along with photographic records. Bio-retention rain garden construction invoices are found in *Appendix A*.

4.2.1 Construction sequencing

1. Clear existing traffic island (*Figure 3*).

2. Excavation of traffic island to a depth of six feet (*Figure 4*).
3. Install PVC pipe and diversion weir for inflow from existing roadway inlet to rain garden (*Figure 5*).
4. Excavated soil mixed at a 1:1 ratio with silica sand to create rain garden media (*Figure 6*).
5. Backfill excavated area with four feet of rain garden media (*Figure 7*).
6. Fill and seal existing parking lot inlet (*Figure 8*).
7. Construct two curb cuts with riprap lined channels for rain garden inflow.
8. Fine grading of rain garden.
9. Plant rain garden vegetation and seed surrounding area.
10. Apply shredded hardwood mulch as surface cover (*Figure 9*).

Figure 3. Clearing of existing traffic island

Figure 4. Excavation of traffic island to a depth of six feet

Figure 5. Roadway inlet diversion installation

Figure 6. Excavated soil mixed with silica sand to create rain garden media

Figure 7. Excavated area backfilled with four feet of rain garden media

Figure 8. Filling of existing parking lot inlet

Figure 9. After application of shredded hardwood mulch as surface cover

4.2.2 Construction material inventory

From the analyzed the data an inventory of construction materials and material quantities was developed. These quantities were converted to units of mass for input into LCA process flow modeling software. *Appendix B* contains unit conversion calculations and assumptions used in these calculations. Bio-retention rain garden construction material inventory and material quantities are shown in *Table 1*. Total cost of construction materials were quoted by the contractor as $2,755 (N. Abbonizio Contractors, Inc., 2001). It should be noted that all costs associated with rain garden construction are in 2001 U.S. dollars and have not been adjusted for inflation.

Table 1. Bio-retention rain garden construction phase material quantities

Materials	Quantity	Units
Silica Sand	225,800	lbs
Pipe (Corrugated HDPE)	40	lbs
Cement	838	lbs
Asphalt	4	lbs
Grass seed	9	lbs
Stone	12,300	lbs
Mulch	5,220	lbs
Seedlings	180	pieces

In *Table 1*, the "Seedlings" represent all rain garden plantings. A more detailed list of plantings is shown in *Table 2*. The plants chosen for this rain garden are native to the New Jersey Atlantic coast. They were selected for their ability to withstand both dry and ponded water conditions in the rain garden (Emerson and Traver, 2008). These plants were purchased from a local plant nursery. Because the life cycle inventory (LCI) databases available for this study do not include detailed life cycle data for plant species in this rain garden, assumptions were made to equate each plant species with seedlings from a greenhouse for which life cycle data is available through the US LCI Database. These assumptions equate each small tree to one seedling and four plugs to one seedling. The result is 180 seedlings applied to the LCA model. Calculations for seedling equivalents are located in *Appendix B*. Total cost of all plants from the local nursery was $660 (Octoraro Native Plant Nursery, Inc., 2001).

Table 2. Bio-retention rain garden plantings

[redacted]

4.2.3 Construction labor inventory

Direct labor effort and cost associated with the rain garden construction were inventoried for construction phase analysis. This data was gathered from the contractor construction invoice (N. Abbonizio Contractors, Inc., 2001). The results of this analysis are shown in *Table 3*. All costs are in terms of 2001 United States Dollars (USD).

Table 3. Bio-retention rain garden construction phase labor

Labor	Quantity	Units	Unit Cost (2001 USD)	Direct Labor Cost (2001 USD)
Laborers	156	hrs	$42	$6,552
Foreman	40	hrs	$55	$2,200
Graduate Student	40	hrs	NA	NA
Total	236	hrs	-	$8,752

4.2.4 Onsite construction equipment inventory

Usage of onsite construction equipment was inventoried using the information derived from the contractor construction invoice (N. Abbonizio Contractors, Inc., 2001). A detailed breakdown of equipment usage is located in *Appendix C. Table 3* summarizes hours of equipment usage and operation costs.

Table 4. Bio-retention rain garden construction phase actual equipment usage

Equipment	Quantity	Units	Unit Cost (2001 USD)	Operation Cost (2001 USD)
Backhoe	40	hrs	$85	$3,400
490 John Deere Excavator	40	hrs	$125	$5,000
Triaxle	32	hrs	$63	$2,000
Saw (consaw/road saw)	12	hrs	$60	$720
Shredder	16	hrs	$150	$2,400
Small Dump Truck	16	hrs	$52	$832
Kawaski Loader	40	hrs	$110	$4,400
Ford Tractor with York Rake	8	hrs	$60	$480
Roller	1	hrs	$55	$55
Total	205	hrs	-	$19,287

The environmental life cycle impacts resulting from the operation of construction equipment has been identified as an information gap in the LCI databases available for use in this study. LCI data was available for excavation activities using a skid-steer loader and a hydraulic digger. These LCI processes were applied to the rain garden construction inventory using an estimated excavation volume of 331 cubic yards, which includes the approximated excavated volume and the imported silica sand volume (Ermilio, 2005). It was assumed that these two processes account for the majority of the environmental impact associated with onsite construction equipment operation. LCA software inputs for these processes are summarized in *Table 5*.

Table 5. Bio-retention rain garden construction phase LCA input of equipment usage

[redacted]

4.2.5 Material and labor transportation inventory

Transportation of materials and labor to the site were inventoried to complete the construction phase LCI. Silica sand and stone were assumed to be transported directly from a local quarry. Rain garden plants were picked up at a local nursery by the Villanova University Facilities Department. All other construction materials were assumed to be transported to the rain garden construction site by the general contractor. Excavated material removed from the site was assumed to be transported by the general contractor as well. Google Maps was used to calculate transportation distances (Google, 2011). All transportation quantities were converted to kilogram-kilometer units. This is the standard unit of transportation measurement used for LCA modeling software input. Transportation quantity calculations and assumptions are located in *Appendix D*. *Table 6* summarizes LCA software process flow modeling inputs.

Table 6. Bio-retention rain garden material and labor transportation LCA inputs

Materials	Vehicle	Distance (km)	Total Payload (kg)	Transportation Units (kgkm)
Silica Sand	Dump Truck	25.9	102,421	2,652,708
Stone	Dump Truck	25.9	5,579	144,501
Excavated material	Dump Truck	13.7	179,300	2,456,411
Cement	Truck	13.7	380	5,205
Asphalt	Truck	13.7	2	27
Grass seed	Truck	13.7	4	59
Mulch	Truck	13.7	2,368	32,438
Seedlings	Truck	85.6	245	20,967
Laborers	Truck	13.7	2,182	29,890
Foreman	Truck	13.7	755	10,347

4.2.6 Construction phase LCIA

TRACI impact categories, as described in Section 3.5 of this paper, are applied to assess the environmental impacts of the bio-retention rain garden construction. SimaPro 7.2 software was used to calculate and compile these TRACI impact categories. Software inputs were derived from the rain garden construction phase inventory and are described in the previous sections of this chapter. Social and economic impact categories were calculated without the use of LCA software. These categories include labor impacts and economic cost. A summary of the bio-retention rain garden construction phase impacts is shown in *Table 7*. Impacts are also shown in terms of the LCA functional unit of "impact per acre of impervious drainage area (DA)." These functional values are calculated based upon a suggested 5:1 impervious drainage area to BMP infiltration area ratio as per *PA BMP Manual* guidelines (PADEP, 2006). Values are linearly interpolated from the calculated rain garden impacts.

Table 7. Bio-retention rain garden construction phase impacts

Impact Category	Unit	Rain Garden Impact	Impact per Acre Impervious DA
Global warming	kg CO2 eq	4,942	9,884
Acidification	H+ moles eq	5,109	10,219
Carcinogenics	kg benzen eq	15	31
Non carcinogenics	kg toluen eq	43,941	87,883
Respiratory effects	kg PM2.5 eq	26	51
Eutrophication	kg N eq	7	14
Ozone depletion	kg CFC-11 eq	0.0004	0.0007
Ecotoxicity	kg 2,4-D eq	1,709	3,419
Smog	g NOx eq	113	226
Onsite labor	hrs	236	472
Cost	2001 USD	31,454	62,908

4.3 Rain garden operation phase

The bio-retention rain garden operation phase LCI consists of inputs and outputs that occur over the operational life of the green infrastructure practice. For this analysis, impacts and benefits are assessed on an annual basis and assumed to project linearly throughout the operational life of the rain garden. Because limited data exists regarding the longevity of rain garden, a 30 year operational life is assumed to assess the system. Additional information regarding the longevity of infiltration practices like the bio-infiltration rain garden can be found in the journal article by Emerson and Traver (2008). The following sections describe these operational inputs and outputs, and the methodologies and assumptions used to assess them.

4.3.1 Maintenance practices

Maintenance conducted at the bio-retention rain garden site is minimal. These maintenance activities include occasional removal of litter and leaves, the removal of invasive plants, and winter clearing of dead woody plant parts. Besides the removal of invasive species and decomposing plant matter, the rain garden vegetation has been left to naturally grow and evolve. Some sediment build-up has occurred along riprap aprons but no sediment removal activities have been necessary as of 2011. Average annual maintenance is estimated at one hour of effort by a two person landscaping crew (Emerson and Traver, 2008). *Table 8* summarizes this annual maintenance effort in terms of labor and cost. A unit labor cost of $42 per hour (2001 USD) was assumed based on the actual general contractor unit costs incurred during construction. Although labor unit costs may differ in an institutional setting such as Villanova University, labor cost quoted by the general contractor may be more representative of most practices throughout the Philadelphia area.

Table 8. Bio-retention rain garden average annual maintenance

Labor	Quantity	Units	Unit Cost (2001 USD)	Direct Labor Cost (2001 USD)
Laborers	2	hrs	$42	$84

Over an assumed 30 year operational life, total labor impacts are estimated at 60 labor hours and a net present value of $2,520 (2001 USD). Environmental life cycle impacts associated with maintenance activities were not accounted for in this analysis. These impacts were deemed insignificant and would most likely be less than a traditionally landscaped traffic island, which in addition to scheduled clearing may require application of fertilizers and mulches.

4.3.2 Urban forest benefits

Over the operational life of the practice, the bio-retention rain garden vegetation provides urban forest benefits such as carbon sequestration and air quality improvement. To assess these benefits the U.S. Forest Service's i-Tree Eco model was utilized. A detailed vegetation surveys was undertaken at the bio-retention rain garden to collect input data for this urban forest model. This survey was conducted on October 8, 2010, and includes an inventory of all land covers, trees, and shrubs. *Figure 10* shows the bio-retention rain garden on the date of the survey.

Figure 10. Bio-retention rain garden at time of vegetation survey

To conduct the survey, the site was divided into forty survey sub-plots of 9 square meters. Each sub-plot was surveyed individually for trees and for shrub cover as per the *i-Tree Eco: User's Manual* (US Forest Service, 2010). The survey boundaries and the survey sub-plot layout are shown in *Figure 11*.

Figure 11. Bio-retention rain garden vegetation survey layout (Not to scale)

Survey results for each sub-plot were combined into a single plot for model input. A summary of vegetation for entire survey area is shown in *Table 9*. Model inputs and detailed survey data for each sub-plot are located in *Appendix E*. As the vegetation has been allowed to develop naturally in the rain garden, the plant species were found to differ slightly from the original plantings. For species not listed in the U.S. Forest Service Database, the nearest species match with available data was assumed. Air pollution and metrological data from the Philadelphia International Airport weather station (Weather Station ID 724080-13739) was utilized for the bio-retention rain garden i-Tree Eco model.

Table 9. Bio-retention rain garden vegetation survey summary

	%Tar	%Rock	%Main. Grass
Ground Cover	1.57	4.01	46.30

	Species	Height (ft)	% Total Area	% Shrub Area
Shrubs	Mugwort	6.5	14.83	30.80
	Aster	3.5	10.00	20.77
	Golden Rod	9	1.50	3.12
	Switch Grass	4	13.80	28.66
	Box Elder	3	0.13	0.27
	Little Blue Stem	5.5	5.63	11.69
	Smartweed	2	1.25	2.60
	Green Foxtail	5.5	0.63	1.31
	White Snakeroot	1	0.38	0.79

				Height (ft)		
	Species	DR (deg)	DS (ft)	Total Height	Live Top	Crown Base
Trees	Beech Plum	82	28.58	9.5	9.5	2
	Winterberry	83	30.95	7	7	2
	Beech Plum	83	33.55	7	7	1
	Sycamore	245	19.3	7.5	7.5	2
	Winterberry	230	10.68	8.5	8.5	2
	Black Chokeberry	130	15.13	9	8	2.5
	Groundsel Tree	56	6.75	11	11	3
	Groundsel Tree	76	5.84	6	6	1
	Winterberry	227	3.37	6	6	3
	Winterberry	291	8.93	8	8	2

Urban forest model data was processed by the U.S. Forest Service. Information regarding model calculations for carbon storage, carbon sequestration, and air pollutant removal by vegetation can be found in the *i-Tree Eco: User's Manual* (US Forest Service, 2010) and Nowak et al. (2006). It should be noted that carbon storage and sequestration results are for trees only, while air pollutant removal results account for both trees and shrubs (US Forest Service, 2010).

The bio-retention rain garden model results are summarized in the flowing figure and tables. *Figure 12* illustrates the predicted monthly air pollutant removal by the rain garden vegetation, and *Table 10* summarizes these predicted air pollutant removals on an annual basis. *Table 11* summarizes the predicted annual carbon storage, carbon sequestration, and avoided global warming potential due to the rain garden vegetation. Carbon storage and carbon sequestration were normalized to calculate the predicted annual avoided global warming potential using the US EPA's *Greenhouse Gas Equivalencies Calculator* (US EPA, 2011).

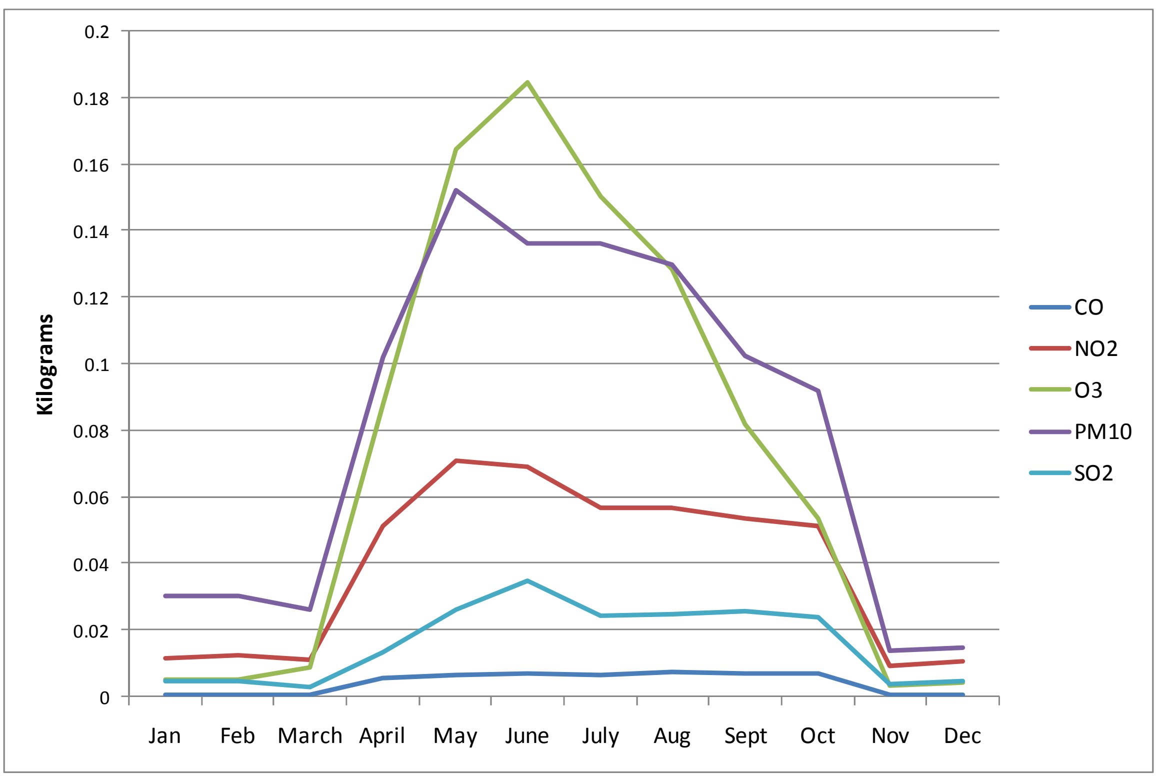

Figure 12. Bio-retention rain garden vegetation monthly air pollutant removal

Table 10. Bio-retention rain garden vegetation annual air pollutant removal

Air Pollutant	Annual Removal by Vegetation	Units
CO	0.05	kg
NO2	0.47	kg
O3	0.88	kg
PM10	0.97	kg
SO2	0.20	kg

Table 11. Bio-retention rain garden annual carbon storage and sequestration by trees

Parameter	Value	Units
Annual Carbon Storage	490	kg C
Annual Carbon Sequestration	40	kg C
Annual Avoided Global Warming Potential	1,943	kg CO2 eq

4.3.3 Stormwater management benefits

As described previously in this chapter, the bio-retention rain garden is equipped with flow monitoring and water quality sampling equipment. This green infrastructure practice has been continuously studied and monitored since 2003. Data includes continuous inflow and outflow measurements and influent and effluent water quality. For this study, bio-retention rain garden performance data was analyzed to develop values representing average annual volume, sediment, and nutrient removals. This analysis uses a mass balance approach and utilizes total annual inflow and outflow volumes and inflow and outflow event mean concentrations (EMCs) of sediments and nutrients. *Table 12* summarizes the calculated average annual stormwater management performance of the bio-retention rain garden for stormwater volume, total suspended solids (TSS), total dissolved solids (TDS), total nitrogen (TN), and total phosphorous (TP). The table also lists the number of years of data the average annual value of each constituent is calculated from. Detailed average annual stormwater management performance calculations are located in *Appendix G*. Further information regarding the Villanova University bio-retention rain garden performance and monitoring program can be found in Prokop (2003), Ermilio (2005), Heasom (2006), and at the Villanova Urban Stormwater Partnership Website (VUSP, 2011).

Table 12. Bio-retention rain garden stormwater management performance

Constituent	Average Annual Removal	Units	Years of Data
Volume	34,350	cf	8
TSS	422.11	kg	8
TDS	782.54	kg	8
TN	1.75	kg	4
TP	1.13	kg	8

Over an assumed 30 year operational life, total projected stormwater management performance includes the removal of approximately 1,030,500 cubic feet of stormwater runoff volume; 12,700 kg of TSS; 23,500 kg of TDS; 52 kg of TN; and 34 kg of TP. These projections assume the bio-retention rain garden maintains a similar level of stormwater management performance over its entire operational life. This assumption may be suspect as the accumulation of sediment will reduce infiltration performance over time. Further research and monitoring would be necessary to predict degradation of performance over time.

4.3.4 Combined sewer system benefits

The Villanova University bio-retention rain garden is located in a separate sewer area. If this green infrastructure practice were located in a combined sewer area, the rain garden would provide additional benefits by reducing volume to a downstream wastewater treatment plant. To be representative of green infrastructure practices in Philadelphia, the hypothetical situation of the bio-retention rain garden in a combined sewer area was investigated. Energy savings due to reduced volume at a wastewater treatment plant and the resulting avoided environmental impacts were quantified for this investigation. Additional environmental impacts could also be avoided through a reduction in combined sewer overflow events, but these impacts were not quantified for this hypothetical assessment.

Energy saving were calculated assuming that a typical medium sized wastewater treatment plant in the U.S. consumes 1,200 kWh per million gallons (MG) of wastewater (Water Environmental Federation, 2009). As calculated in Section 4.3.3, the average annual volume removal for the bio-retention rain garden is 34,350 cubic feet. Based upon the assumption of a typical medium sized wastewater treatment plant, the bio-retention rain garden may result in an avoided energy use of 308 kWh. Using SimaPro's Ecoinvent Database process for US energy production, annual avoided environmental impacts were calculated for all TRACI impact categories (PRé Consultants, 2010). *Table 13* summarizes these annual avoided impacts for the bio-retention rain garden in a hypothetical combined sewer area.

Table 13. Bio-retention rain garden combined sewer system avoided impacts

Impact Category	Unit	Avoided Annual Impact	Impact per Acre Impervious DA
Global warming	kg CO2 eq	-232	-464
Acidification	H+ moles eq	-83	-165
Carcinogenics	kg benzen eq	-0.56	-1.11
Non carcinogenics	kg toluen eq	-3,760	-7,519
Respiratory effects	kg PM2.5 eq	-0.44	-0.88
Eutrophication	kg N eq	-0.88	-1.77
Ozone depletion	kg CFC-11 eq	-0.000006	-0.000012
Ecotoxicity	kg 2,4-D eq	-672	-1,344
Smog	g NOx eq	-0.45	-0.90

4.3.5 Operation phase LCIA

TRACI impact categories are applied to assess the total environmental impacts and benefits of the bio-retention rain garden operation phase. As in the construction phase, SimaPro 7.2 software was used to calculate and compile these TRACI impact categories. Social and economic impact categories were calculated without the use of LCA software. A 30 year operational life was assumed for all operation phase calculations.

A summary of the bio-retention rain garden operation phase impacts is shown in *Table 14*. All annual impacts were projected linearly over an assumed 30 year operation phase of the bio-retention rain garden. Negative values indicate avoided environmental impact. These values assume the hypothetical combined sewer condition. Contributions to these calculated operational phase impacts include cost and labor associated with onsite maintenance activities (Section 4.3.1); reduced global warming potential through carbon storage and sequestration by vegetation (Section 4.3.2); reduced eutrophication potential through rain garden effluent nitrogen removal (Section 4.3.3); and avoided environmental impacts of reduced energy use at a wastewater treatment plant (Section 4.3.4). A one year period to establish vegetation was assumed for calculating total reduced global warming potential. The eutrophication potential for aquatic systems where phosphorous is the limiting nutrient was not examined in this analysis. This is a significant benefit as most freshwater aquatic environments will be phosphorous limited but impact assessment beyond TRACI environmental impact categories is beyond the scope of this study (Finnveden and Potting, 1999). As described in Section 4.3.1, environmental impacts associated with onsite maintenance activities were deemed insignificant and not accounted for in this assessment. Impacts are also shown in terms of the LCA functional unit of "impact per acre of impervious drainage area (DA)." These functional values are calculated based upon a suggested 5:1 impervious drainage area to BMP infiltration area ratio as per *PA BMP Manual* guidelines (PADEP, 2006).

Table 14. Bio-retention rain garden operation phase impacts (30 Years)

Impact Category	**Unit**	**Rain Garden Impact**	**Impact per Acre Impervious DA**
Global warming	kg CO2 eq	-63,304	-126,608
Acidification	H+ moles eq	-2,476	-4,953
Carcinogenics	kg benzen eq	-16.69	-33.39
Non carcinogenics	kg toluen eq	-112,790	-225,580
Respiratory effects	kg PM2.5 eq	-13.14	-26.27
Eutrophication	kg N eq	-78.90	-157.80
Ozone depletion	kg CFC-11 eq	-0.000185	-0.000369
Ecotoxicity	kg 2,4-D eq	-20,154	-40,308
Smog	g NOx eq	-13.43	-26.86
Onsite labor	hrs	60	120
Cost	2001 USD	1,260	2,520

An analysis was also performed to compare construction phase environmental impacts to operation phase environmental impacts. Operation phase avoided impacts were projected beyond the assumed 30 year operational life of the bio-retention rain garden in order to predict a point where each construction phase impact category would be offset. These projected environmental impact break-even points ranged from just 3 years for eutrophication and ecotoxicity potential, to 253 years for smog formation potential. Of the assessed environmental impact categories, the construction impacts with regard to global warming, carcinogenics, non carcinogenics, eurtrophication, and ecotoxicity potential are all projected to be offset of the assumed 30 year operational life of the bio-retention rain garden. These projected construction offset points are summarized in *Table 15*. Calculations can be found in *Appendix H*.

Table 15. Bio-retention rain garden projected construction environmental impact offset

Impact Category	Projected Break-Even Year
Global warming	4
Acidification	62
Carcinogenics	28
Non carcinogenics	12
Respiratory effects	59
Eutrophication	3
Ozone depletion	59
Ecotoxicity	3
Smog	253

4.4 Rain garden decommissioning phase

As of the publication of this study (2011), the Villanova University bio-retention rain garden is in the operation phase of its life cycle. Limited information and research is available on the decommissioning of green infrastructure practices such as rain gardens. It is assumed that the need for decommissioning or refurbishment of a rain garden would be due to significantly degraded stormwater management performance. This degradation in performance may be caused by clogging of rain garden media attributable to sediment deposition and by accumulation of nutrients, metals, and other pollutants that would reduce water quality improvement (Emerson and Traver, 2008). For this study, it is assumed that the decommissioning of the bio-retention rain garden would consist of the removal of the rain garden media. Media replacement is beyond the defined system boundary of this life cycle assessment.

Because a decommissioning plan does not exist for the bio-retention rain garden, two decommissioning scenarios were examined. Scenarios assessed include a rain garden media reuse scenario and a rain garden media disposal scenario. LCIs for these scenarios are described in the following sections.

4.4.1 Rain garden media reuse scenario

The bio-retention rain garden media reuse decommissioning scenario assumes the onsite reuse of all rain garden media. This rain garden media could potentially be used by the Villanova University Facilities Department as fill material for other on campus construction projects. LCI for this decommissioning scenario includes the material and energy flows and the labor hours and cost associated with the excavation of the rain garden media.

As in the rain garden construction phase, LCI processes for excavation activities using a skid-steer loader and a hydraulic digger were applied using SimaPro 7.2 software. An excavation volume of 167 cubic yards was estimated to account for the removal of all rain garden media (Ermilio, 2005). *Table 16* summarizes LCA software inputs for decommissioning excavation. It was assumed that these two processes account for the majority of the environmental impact associated with onsite construction equipment operation during decommissioning.

Table 16. Bio-retention rain garden decommissioning phase excavation LCA input

Process	Quantity	Units
Excavation, skid-steer loader	167	cu.yd
Excavation, hydraulic digger	167	cu.yd

The assumption was made that decommissioning of the bio-retention rain garden is accomplished in two 8-hour work days by a team of two laborers, with 8 hours of foreman supervision. Unit costs (2001 USD) for labor and equipment operation were derived from the contractor construction invoice (N. Abbonizio Contractors, Inc., 2001). *Table 17* summarizes direct labor effort and cost, and *Table 18* summarizes hours of equipment usage and operation costs.

Table 17. Bio-retention rain garden decommissioning phase labor

Labor	Quantity	Units	Unit Cost (2001 USD)	Direct Labor Cost (2001 USD)
Laborers	32	hrs	$42	$1,344
Foreman	8	hrs	$55	$440
Total	40	hrs	-	$1,784

Table 18. Bio-retention rain garden decommissioning phase equipment usage

Equipment	Quantity	Units	Unit Cost (2001 USD)	Operation Cost (2001 USD)
490 John Deere Excavator	16	hrs	$125	$2,000
Kawaski Loader	16	hrs	$110	$1,760
Total	32	hrs	-	$3,760

4.4.2 Rain garden media disposal scenario

The bio-retention rain garden media disposal decommissioning scenario assumes the disposal of all rain garden media and all construction materials. LCI for this decommissioning scenario includes SimaPro's Ecoinvent Database process for waste disposal and landfill of municipal waste in the U.S. This database process is based on data from U.S. EPA data (PRé Consultants, 2010). Media excavation LCI inputs are assumed to be the same as the rain garden media reuse decommissioning scenario. Additional cost is included in this scenario for the removal of the rain garden media from the site. This additional decommissioning cost was estimated using the contractor construction invoice and is summarized in *Table 19* (N. Abbonizio Contractors, Inc., 2001).

Table 19. Bio-retention rain garden media removal cost

Process	Quantity	Units	Unit Cost (2001 USD)	Hauling Cost (2001 USD)
Material Removal	6	loads	$75	$450

4.4.3 Decommissioning phase LCIA

TRACI impact categories are applied to assess the environmental impacts of the bio-retention rain garden decommissioning phase scenarios. SimaPro 7.2 software was used to calculate and compile these TRACI impact categories. Social and economic impact categories were calculated without the use of LCA software. *Table 20* summarizes the rain garden media reuse decommissioning phase scenario, and *Table 21* summarizes the rain garden media disposal decommissioning phase scenario. Impacts are also shown in terms of the LCA functional unit of "impact per acre of impervious drainage area (DA)."

Table 20. Bio-retention rain garden decommissioning phase impacts - media reuse

Impact Category	Unit	Rain Garden Impact	Impact per Acre Impervious DA
Global warming	kg CO2 eq	134	269
Acidification	H+ moles eq	72	144
Carcinogenics	kg benzen eq	0.07	0.14
Non carcinogenics	kg toluen eq	552	1,104
Respiratory effects	kg PM2.5 eq	0.27	1
Eutrophication	kg N eq	0.18	0.37
Ozone depletion	kg CFC-11 eq	0.000016	0.000033
Ecotoxicity	kg 2,4-D eq	44	88
Smog	g NOx eq	1.56	3.11
Onsite labor	hrs	40	80
Cost	2001 USD	5,544	11,088

Table 21. Bio-retention rain garden decommissioning phase impacts - media disposal

Impact Category	Unit	Rain Garden Impact	Impact per Acre Impervious DA
Global warming	kg CO2 eq	51,291	102,581
Acidification	H+ moles eq	1,340	2,680
Carcinogenics	kg benzen eq	17,227.32	34,454.63
Non carcinogenics	kg toluen eq	557,313,182	1,114,626,364
Respiratory effects	kg PM2.5 eq	4.07	8
Eutrophication	kg N eq	631.85	1,263.70
Ozone depletion	kg CFC-11 eq	0.000378	0.000756
Ecotoxicity	kg 2,4-D eq	4,158,604	8,317,209
Smog	g NOx eq	28.55	57.10
Onsite labor	hrs	40	80
Cost	2001 USD	5,994	11,988

4.5 Rain garden complete LCIA

To assess the complete life cycle impact of the Villanova University bio-retention rain garden, the results from each life cycle phase were combined for analysis. Complete life cycle impacts were assessed for both decommissioning phase scenarios. *Table 22*summarizes complete life cycle impacts utilizing the media reuse decommissioning scenario, and *Table 23* summarizes the complete life cycle impacts for the media disposal decommissioning scenario. Negative values represent avoided environmental impacts. Detailed total bio-retention rain garden life cycle impact calculations can be found in *Appendix I*.

Table 22. Bio-retention rain garden total life cycle impact - media reuse

Impact Category	Unit	Total LCA Impact	Impact per Acre Imp. DA
Global warming	kg CO2 eq	-58,228	-116,456
Acidification	H+ moles eq	2,705	5,411
Carcinogenics	kg benzen eq	-1.26	-2.51
Non carcinogenics	kg toluen eq	-68,297	-136,594
Respiratory effects	kg PM2.5 eq	12.82	25.64
Eutrophication	kg N eq	-71.92	-143.84
Ozone depletion	kg CFC-11 eq	0.000192	0.000383
Ecotoxicity	kg 2,4-D eq	-18,401	-36,801
Smog	g NOx eq	101.06	202.12
Onsite labor	hrs	336	672
Cost	2001 USD	38,258	76,516

Table 23. Bio-retention rain garden total life cycle impact - media disposal

Impact Category	Unit	Total LCA Impact	Impact per Acre Imp. DA
Global warming	kg CO2 eq	-7,071	-14,143
Acidification	H+ moles eq	3,973	7,947
Carcinogenics	kg benzen eq	17,226	34,452
Non carcinogenics	kg toluen eq	557,244,333	1,114,488,666
Respiratory effects	kg PM2.5 eq	16.62	33.23
Eutrophication	kg N eq	559.75	1,119.50
Ozone depletion	kg CFC-11 eq	0.000553	0.001106
Ecotoxicity	kg 2,4-D eq	4,140,160	8,280,320
Smog	g NOx eq	128.05	256.11
Onsite labor	hrs	336	672
Cost	2001 USD	38,708	77,416

Under the media reuse decommissioning scenario, the bio-retention rain garden provides net total benefits towards global warming potential, carcinogenics, non carcinogenics, eutrophication potential, and ecotoxicity. The act of disposing of the rain garden media to a landfill in the media disposal decommissioning scenario negates all of these avoided environmental impacts with the exception of global warming potential. Chapter 6 provides further interpretation and analysis of the bio-retention rain garden life cycle assessment.

CHAPTER 5: GREEN ROOF LIFE CYCLE ASSESSMENT

5.1 Villanova University Green Roof

The green roof selected in this study for life cycle assessment is the Villanova University green roof located on the Center for Engineering Education and Research (CEER) building. This extensive green roof was constructed in July 2006, as a retrofit to 576 square foot portion of the CEER building roof (Rudwick, 2008). The CEER building is located on the Villanova University campus in southeastern Pennsylvania, within the Darby-Cobbs Watershed. This green roof captures direct precipitation only and was designed to retain up to 1.85 inches of rainfall (Schneider, 2011).

Data gathering techniques for life cycle assessment of the CEER green roof include engineering plans, contractor invoices, onsite inspection, interviews with professionals involved in the design and construction, published literature, and the analysis of photographic records. The LCA of the CEER green roof follows the methodology described in Chapter 3 and demonstrated in Chapter 4 of this paper.

5.2 Green roof construction phase

Green roof construction took place July 2006. This green infrastructure practice was designed by Green Roof Service, LLC in conjunction with the Villanova University Department of Civil and Environmental Engineering. Construction was carried out by a local general contractor with assistance from the Villanova University Facilities Department (Rudwick, 2008). Construction costs for the CEER green roof total to

$44,597 (2006 USD). This total cost includes all construction materials and labor as well as architectural fees (Villanova University Facilities Department, 2006).

As a research site, the CEER green roof was equipped with a rain gauge, flow monitoring, and temperature monitoring equipment. The manufacturing and installation of this equipment was deemed beyond the scope of the study and is purposefully excluded from this life cycle assessment. This equipment is not essential to the implementation and function of a green roof and inclusion in the study would not be representative of a green infrastructure practice outside of a research setting.

To inventory the material and energy flows for the construction life cycle phase of the bio-retention rain garden, data was collected primarily using the construction plans, the Green Roof Service, LLC components and specifications memo (2006), and analysis of photographic records. The general construction phase sequencing derived from this data is listed in the following section, along with photographic records. CEER green roof construction documents are found in *Appendix J*.

5.2.1 Construction sequencing

1. Prepare existing roof for retrofit (*Figure 13*).
2. Reseal existing roof with tar (*Figure 14*).
3. Install building protection matting (*Figure 15*).
4. Install foam insulation layer and impermeable membrane layer (*Figure 16*).
5. Construct retaining edge drain (*Figure 17*).
6. Install drainage layer and filter fabric layer (*Figure 18*).
7. Apply and spread 4 inches of green roof media (*Figure 19*).
8. Add stone to green roof edge drain (*Figure 20*).

9. Plant, fertilize, and water green roof vegetation (*Figure 21*).

Figure 13. Existing roof before green roof retrofit

Figure 14. Resealing of existing roof

Figure 15. Installation of building protection matting

Figure 16. Installation of insulation and impermeable membrane

Figure 17. Retaining edge drain construction

Figure 18. Installation of drainage and filter fabric layers

Figure 19. Application of green roof media

Figure 20. Addition of stone to green roof edge drain

Figure 21. Planting of green roof vegetation

5.2.2 Construction material inventory

From the analyzed the green roof data, an inventory of construction materials and material quantities was developed. These quantities were converted to units of mass for input into LCA process flow modeling software. *Appendix K* contains unit conversion calculations and assumptions used in these calculations. Green roof construction material inventory and material quantities are shown in *Table 24*.

Table 24. Green roof construction phase material quantities

Materials	Quantity	Units
Roofing Tar/Sealant	195	lbs
Polystyrene Foam Insulation	173	lbs
Building Protection Mat	52	lbs
Drainage Layer (HDPE)	156	lbs
Filter Fabric	10	lbs
Retaining Edge Drain	2,531	lbs
Green Roof Media	3,445	lbs
Stone	3,200	lbs
Green Roof Plants (Sedums)	390	pieces
Fertilizer	4	lbs

The green roof building protection mat, drainage layer, filter fabric, retaining edge drain, and fertilizer were all manufactured by Optigreen Internation AG. Optigreen is a worldwide leader in the supply and manufacturing of green roof components (Green Roof Service, LLC, 2006). Material quantity calculations for these Optigreen products are based on manufacturer specifications (Optigreen International AG, 2011). Stone for lining of the retaining edge drain was assumed to be sourced from a local quarry. The media used on the CEER green roof is Rooflite® Extensive MC. This is an engineered media, produced by Skyland USA, LLC, designed specifically for green roofs. Sedums plants were chosen by the designers due to their ability to thrive in both dry and saturated conditions (Schneider, 2011). Because the life cycle inventory (LCI) databases available for this study do not include detailed life cycle data for sedums, it was assumed that four sedum plugs have the equivalent life cycle impacts to one seedling. Detailed calculations and assumptions are located in *Appendix K.*

5.2.3 Construction labor inventory

Direct labor effort and cost associated with the green roof construction were inventoried for construction phase analysis. Labor was estimated based upon analysis of photographic records. Because detailed construction unit costs for the green roof were not available, labor cost was estimated based upon general contractor unit cost applied for the bio-retention rain garden construction (N. Abbonizio Contractors, Inc., 2001). Labor unit costs were adjusted for inflation and estimated in terms of 2006 US Dollars in order to be consistent with other construction costs (US Inflation Calculator, 2011). The results of this analysis are shown in *Table 25*.

Table 25. Green roof construction phase labor inventory

Labor	Quantity	Units	Unit Cost (2006 USD)	Direct Labor Cost (2006 USD)
Laborers	64	hrs	$47.80	$3,059
Foreman	16	hrs	$62.64	$1,002
Graduate Student	16	hrs	NA	NA
Total	96	hrs	-	$4,061

5.2.4 Onsite construction equipment inventory

Usage of onsite construction equipment was inventoried using the information derived from the analysis of photographic records. *Table 26* summarizes estimated hours of equipment usage. Operation unit cost information was not available.

Table 26. Green roof construction phase onsite equipment usage

Equipment	Quantity	Units
Terex TH844C Turbo - Rough Terrain Telescopic Boom Material Handler	16	hrs
Tar trailer and boiler	8	hrs
Total	24	hrs

The environmental life cycle impacts resulting from operation of a telescopic boom material handler and a tar trailer and boiler are not part of the LCI databases available for use in this study. The assumption was made that operation of a material handler is similar to that of a skid-steer loading. Therefore, the skid-loader LCI process was applied to the green roof construction inventory using an estimated material volume of 97 cubic yards. This volume is based on the volume of green roof media and stone which both moved to the roof during construction by the telescopic boom material handler. Due to lack of an equivalent LCI process, the operation of the tar trailer and boiler was excluded from the rain garden construction phase LCI.

5.2.5 Material and labor transportation inventory

Transportation of materials and labor to the green roof site were inventoried to complete the construction phase LCI. All Optigreen green roof components used for the construction of the CEER green roof were manufactured in Germany, and represent the most significant transportation impact associated with the green roof construction. The transportation route assumed for these components is as follows: ground shipping from the Optigreen facility in Krauchewies, Germany to the Port of Rotterdam, Netherlands; shipping by ocean freight from Rotterdam to Baltimore, MD; and finally ground shipping from Optigreen's warehouse in Baltimore to the project site at Villanova University (Optigreen International AG, 2011).

Green roof media was sourced from Skyland USA, LCC (Feller, 2011). Stone was assumed to be transported directly from a local quarry. Green roof plants are from Emory Knoll Farms in Street, MD. All other construction materials were assumed to be transported to the green roof construction site by the general contractor. Google Maps was used to calculate all ground transportation distances (Google, 2011). Sea freight shipping distance was calculated using an online shipping route calculation tool (SeaRate Freight Exchange, 2011). All transportation quantities were converted to kilogram-kilometer units for LCA modeling software input. Green roof construction phase transportation quantity calculations and assumptions can be found in *Appendix L*. *Table 27* summarizes LCA software process flow modeling inputs.

Table 27. Green roof material and labor transportation LCA inputs

Materials	Vehicle	Distance (km)	Total Payload (kg)	Transportation Units (kgkm)
Optigreen Green Roof Components (Krauchenwies to Rotterdam)	Truck	720	2,753	899,280
Optigreen Green Roof Components (Rotterdam to Baltimore)	Sea Freight	6,612	2,753	8,258,388
Optigreen Green Roof Components (Baltimore to Villanova)	Truck	135	2,753	168,615
Green Roof Media	Truck	50	3,445	78,131
Stone	Truck	26	3,200	37,739
Green Roof Plants (Sedums)	Truck	95	390	16,806
Laborers	Truck	14	1,480	9,197
Foreman	Truck	14	370	2,299

5.2.6 Construction phase LCIA

TRACI impact categories are applied to assess the environmental impacts of the CEER green roof construction phase. SimaPro 7.2 software was used to calculate and compile these TRACI impact categories. Social and economic impact categories were calculated without the use of LCA software. Impacts are also shown in terms of the LCA functional unit of "impact per acre of impervious drainage area (DA)." These functional unit values are calculated based upon a 1:1 impervious drainage area to green roof area. Values are linearly interpolated from the calculated green roof impacts. It is noted that a linear interpolation up to an acre may not be appropriate because of the relatively small size of the actual green roof. *Table 28* summarizes the green roof total construction phase impacts.

Table 28. Green roof construction phase impacts

Impact Category	Unit	Rain Garden Impact	Impact per Acre Impervious DA
Global warming	kg CO2 eq	7,603	636,932
Acidification	H+ moles eq	1,434	120,156
Carcinogenics	kg benzen eq	37	3,068
Non carcinogenics	kg toluen eq	203,781	17,070,597
Respiratory effects	kg PM2.5 eq	9	713
Eutrophication	kg N eq	20	1,681
Ozone depletion	kg CFC-11 eq	0.0004	0
Ecotoxicity	kg 2,4-D eq	29,521	2,472,982
Smog	g NOx eq	15	1,240
Onsite labor	hrs	96	8,042
Cost	2006 USD	44,597	3,735,861

5.3 Green roof operation phase

The CEER green roof operation phase LCI consists of inputs and outputs that occur over the operational life. For this analysis, impacts and benefits are assessed on an annual basis and assumed to project linearly throughout the operational life of the green infrastructure practice. A conventional roofing system requires major maintenance or replacement ever 10 to 15 years. By protecting roofing systems from weather and ultraviolet (UV) rays, green roofs have an increased the operational life compared to traditional roofs. North American roofing companies project a minimal operational life of 25 years for extensive green roofs, like the CEER green roof (Kosareo and Ries, 2007). While green roofs have only become popular in the U.S. of the past few decades, they have been implemented in European countries for centuries (Schneider, 2011). European researchers have observed green roof systems with life spans of over 50 years (Kosareo and Ries, 2007). For this study, an operational life of 30 years is assumed to assess the system. While research suggests the life of green roof systems could be anywhere from 25 to 50 plus years, a 30 year practice life seems to be an conservative estimate and also allows for direct comparison to other green infrastructure practices, such as the bio-retention rain garden. The following sections describe CEER green roof operational inputs and outputs, and the methodologies and assumptions used to assess them.

5.3.1 Maintenance practices

Extensive green roof annual maintenance is minimal. Typical annual maintenance is limited to weeding a fertilizing. These maintenance activities are estimated at one hour of annual effort by a single landscaping professional. Optigreen extensive roof fertilizer is applied twice a year at the recommended rate of 4 pounds per 1000 square feet. Cost of this green specific fertilizer is $160 (2008 USD) for a 55 pound bag (Philippi, 2008). This equates to approximately 4.2 pounds of fertilizer annually and a cost, adjusted for inflation, of $11.44 (2006 USD) per year for the CEER green roof (US Inflation Calculator, 2011).

In 2011, the CEER green roof required its vegetation to be partially replanted due to periods of drought. For this experience, it is assumed that partial replanting will be required every five years of the green roof life cycle. It is also assumed that this replanting will be of approximately 25% of the originally planted green roof vegetation or approximately 390 sedum plugs. Annualized this is 78 sedums per year for replanting, which equates to approximately 20 seedlings per year for LCA software input. Unit cost for sedum plugs were estimated at $0.61 (2006 USD) per plug from the original green roof planting plan. Labor effort for replanting was estimated at two hours every five years, annualized to 0.4 hours per year. *Table 28* summarizes the material and labor inventory for green roof maintenance on an annual basis. Total estimated maintenance cost for the CEER green roof are estimated at $125.94 per year (2006 USD).

Table 29. Green roof annualized maintenance materials and labor

Materials/Labor	Quantity	Units	Unit Cost (2006 USD)	Direct Cost (2006 USD)
Fertilizer	4.2	lbs	$2.91	$11.44
Green Roof Plants (Sedums)	78	plugs	$0.61	$47.58
Laborers	1.4	hrs	$47.80	$66.92

Also considered in this analysis were the avoided maintenance impacts that are associated with a traditional roof. It was assumed that the roof membrane of a traditional roof would be replaced every 15 years. These quantities were assumed equivalent to those of the roofing tar/sealant and building protection mat used for construction as described in Section 5.2.5 of this paper. These quantities were annualized for this analysis, and the resulting values are listed in *Table 30*. Avoided impacts associated with the disposal of these roofing materials were considered as well. It was assumed that both the tar/sealant and roofing membrane are sent to a landfill for disposal. Cost and labor associated with these avoided impacts was excluded from this analysis.

Table 30. Green roof annual avoided maintenance materials verses a traditional roof

Materials	Quantity	Units
Roofing Tar/Sealant	13	lbs
Roofing Membrane	3	lbs

Annual maintenance impacts and avoided maintenance impacts were calculated using SimaPro 7.2 software. Impacts and avoided impacts were then combined to calculate net annual LCA maintenance impacts. *Table 31* summarizes these LCIA results. This analysis shows that a green roof results in a net annual benefit for all TRACI environmental impact categories when incorporating the avoiding impacts of traditional roof maintenance.

Table 31. Green roof maintenance net annual impacts

Impact Category	Unit	Maintenance	Avoided Maintenance	Net LCA Impact	Impact per Acre Imp. DA
Global warming	kg CO2 eq	3.70	-9.97	-6.27	-525.40
Acidification	H+ moles eq	1.94	-2.31	-0.37	-31.16
Carcinogenics	kg benzen eq	0.001	-0.939	-0.938	-78.564
Non carcinogenics	kg toluen eq	24	-30,236	-30,213	-2,530,885
Respiratory effects	kg PM2.5 eq	0.0085	-0.0101	-0.0015	-0.1298
Eutrophication	kg N eq	0.0003	-0.0608	-0.0605	-5.0643
Ozone depletion	kg CFC-11 eq	0.0000000005	-0.0000029830	-0.0000029825	-0.0002498414
Ecotoxicity	kg 2,4-D eq	0.36	-228.02	-227.66	-19,071.25
Smog	g NOx eq	0.0030	-0.0182	-0.0153	-1.2782
Onsite labor	hrs	1.4	-	1.4	117.3
Cost	2006 USD	125.94	-	125.94	10,549.90

5.3.2 Urban forest benefits

Like the bio-retention rain garden, the green roof vegetation provides urban forest benefits such as carbon sequestration and air quality improvement. Unlike the bio-retention LCA, these benefits were not modeled for the green roof. As an extensive green roof, the vegetation on CEER green roof is limited to sedum plants as ground cover. The i-Tree Eco model used to assess the bio-retention rain garden is limited in that it can only calculate carbon storage and sequestration for trees (US Forest Service, 2010). Because of the limitations of this model, carbon storage and sequestration benefits were based on the results of a recent publication on the “Carbon Sequestration Potential of Extensive Green Roofs” by Getter et al. This study assessed twelve extensive green roofs composed primary of sedum species. The results of this study predict an average of 375 grams of carbon per square meter of green roof over a two year period (Getter et al., 2009). Using this value it was estimated that the CEER green roof has the potential to sequester 9058 grams of carbon per year. This equates to an avoided global warming potential of 33.2 kilograms of carbon dioxide equivalent per year (US EPA, 2011). These calculations are summarized in *Table 32*. *Figure 22* shows the CEER green roof, fully vegetated during its operation phase.

Table 32. Green roof annual avoided global warming potential calculations

Parameter	Value	Units
CEER Green Roof Area	48	sq.m
Extensive Green Roofs Ave. Sequestration - 2 year period	375	g C per sq.m
CEER Green Roof Annual Sequestration	9058	g C per year
CEER Green Roof Annual Avoided Global Warming Potential	33.2	kg CO2 eq per year

Figure 22. Green roof during operation phase (Photo by: Green Roof Services, LLC)

5.3.3 Stormwater management benefits

Although the CEER green roof is equipped with flow monitoring equipment, verified flow data, like that associated with the Villanova University bio-retention rain garden, is not yet available. Stormwater volume retention by green roofs can vary greatly. A range from 10% to 90% volume reduction has been observed worldwide. For this study, the assumption was made that the CEER green roof will provide a 50% reduction in runoff volume. This seems like a conservative estimate as the CEER green roof was originally designed to retain up to 1.85 inches of rainfall (Schneider, 2011). Stormwater volume removal for the green roof was estimated using an annual average precipitation of 42.03 inches per year for the Philadelphia Area (National Weather Service, 2011). These calculations result in a predicted annual stormwater volume removal of 911 cubic feet for the CEER green roof. Although, the green roof will have an effect on stormwater peak flow rates and stormwater quality, these impacts were not quantified in this study.

5.3.4 Combined sewer system benefits

The Villanova University CEER building green roof is located in a separate sewer area. To be representative of green infrastructure practices in Philadelphia, the hypothetical situation of the CEER green roof in a combined sewer area was investigated. Energy savings due to reduced volume at a wastewater treatment plant and the resulting avoided environmental impacts were quantified for this investigation. Additional environmental impacts could also be avoided through a reduction in combined sewer overflow events, but these impacts were not quantified for this hypothetical assessment.

As in the bio-retention rain garden analysis (Section 4.3.4), energy saving were calculated assuming that a typical medium sized wastewater treatment plant in the U.S.

consumes 1,200 kWh per million gallons (MG) of wastewater (Water Environmental Federation, 2009). As calculated in Section 5.3.3, the predicted average annual volume removal for the CEER green roof is 911 cubic feet. Based upon the assumption of a typical medium sized wastewater treatment plant, the CEER green roof may result in an avoided energy use of 8 kWh per year. Using SimaPro's Ecoinvent Database process for US energy production, annual avoided environmental impacts were calculated for all TRACI impact categories (PRé Consultants, 2010). *Table 33* summarizes these annual avoided environmental impacts for CEER green roof in a hypothetical combined sewer area.

Table 33. Green roof combined sewer system avoided environmental impacts

Impact Category	Unit	Avoided Annual Impact	Impact per Acre Impervious DA
Global warming	kg CO2 eq	-6.02	-504.58
Acidification	H+ moles eq	-2.14	-179.60
Carcinogenics	kg benzen eq	-0.014	-1.211
Non carcinogenics	kg toluen eq	-98	-8,180
Respiratory effects	kg PM2.5 eq	-0.01	-0.95
Eutrophication	kg N eq	-0.02	-1.92
Ozone depletion	kg CFC-11 eq	-0.0000002	-0.0000134
Ecotoxicity	kg 2,4-D eq	-17	-1,462
Smog	g NOx eq	-0.01	-0.97

5.3.5 Building energy benefits

Green roofs act to insulate buildings from both daily temperature fluctuations and from extreme temperatures. This can result in reduced building energy demand for heating and air conditioning (Getter et al., 2009). Summer temperature monitoring on the CEER green roof has shown an average temperature differential between the air and green roof surface of 4 degrees Celsius (Rudwick, 2008). To estimate building energy impacts over the green roof operational phase, the Green Building Research Laboratory's Green Roof Energy Calculator was utilized. This online tool was developed through funding by the US Green Building Council to compare annual energy performance of vegetative roofs to conventional roofs as well as highly reflective roofs. Calculations are based upon building location climate, green roof area, building type, growing media depth, leaf area index, and utility rate information (Green Building Research Laboratory, 2011). Green Roof Energy Calculator inputs and assumptions are listed in *Appendix M*. Electric and gas utility rates were assumed at $0.0787 (2011 USD) per kWh and $7.5793 (2011 USD) per mcf respectively. These are based on commercial costumer rates quoted from a local utility provider as of June 1, 2011 (UGI Utilities Inc., 2011). The calculated annual building energy benefits for the CEER green roof verses a conventional roof are summarized in *Table 34*.

Table 34. Green roof annual building energy benefits verses a conventional roof

Parameter	Value	Units
Electrical Savings	81.54	kWh
Gas Savings	6.75	Therms
Total Energy Cost Savings	11.52	2011 USD

Avoided energy use environmental impacts of the CEER green roof verses a traditional roof were calculated using SimaPro 7.2 software. *Table 35* summarizes these LCIA results. To maintain consistency with other aspects of this green roof analysis, energy cost savings were adjusted for inflation to 2006 USD (US Inflation Calculator, 2011).

Table 35. Green roof annual avoided building energy use impacts

Impact Category	Unit	Avoided Annual Impact	Impact per Acre Impervious DA
Global warming	kg CO2 eq	-61.39	-5,142.98
Acidification	H+ moles eq	-21.85	-1,830.54
Carcinogenics	kg benzen eq	-0.147	-12.341
Non carcinogenics	kg toluen eq	-995	-83,378
Respiratory effects	kg PM2.5 eq	-0.12	-9.71
Eutrophication	kg N eq	-0.23	-19.60
Ozone depletion	kg CFC-11 eq	-0.0000016	-0.0001364
Ecotoxicity	kg 2,4-D eq	-178	-14,898
Smog	g NOx eq	-0.12	-9.93
Cost	2006 USD	-10.29	-861.99

5.3.6 Operation phase LCIA

TRACI impact categories are applied to assess the total environmental impacts and benefits of the CEER green roof operation phase. SimaPro 7.2 software was used to calculate and compile these TRACI impact categories. Social and economic impact categories were calculated without the use of LCA software. A 30 year operational life was assumed for all operation phase calculations.

A summary of the rain garden operation phase impacts is shown in *Table 36*. All annual impacts were projected linearly over an assumed 30 year operation phase of the green roof. Negative values indicate avoided environmental impact. All calculated values assume the hypothetical combined sewer condition. Contributions to these calculated operational phase impacts include impacts of maintenance activities (Section 5.3.1); avoided maintenance activities verses a traditional roof (Section 5.3.1); reduced global warming potential through carbon storage and sequestration by green roof vegetation (Section 5.3.2); avoided environmental impacts of reduced energy use at a wastewater treatment plant (Section 5.3.4); and avoided building energy use impacts verses a traditional roof (Section 5.3.5). A one year period to establish vegetation was assumed for calculating total reduced global warming potential. Impacts are also shown in terms of the LCA functional unit of “impact per acre of impervious drainage area (DA).” These functional values are calculated based upon a 1:1 impervious drainage area to green roof area.

Table 36. Green roof operation phase impacts (30 Years)

Impact Category	Unit	Green Roof Impact	Impact per Acre Impervious DA
Global warming	kg CO2 eq	-3,174	-265,842
Acidification	H+ moles eq	-731	-61,239
Carcinogenics	kg benzen eq	-32.99	-2,763.45
Non carcinogenics	kg toluen eq	-939,167	-78,673,315
Respiratory effects	kg PM2.5 eq	-3.87	-323.77
Eutrophication	kg N eq	-9.52	-797.61
Ozone depletion	kg CFC-11 eq	-0.000143	-0.011990
Ecotoxicity	kg 2,4-D eq	-12,689	-1,062,942
Smog	g NOx eq	-4.36	-365.37
Onsite labor	hrs	42	3,518
Cost	2006 USD	3,470	290,637

Further analysis was performed to compare construction phase environmental impacts to operation phase environmental impacts. Operation phase avoided impacts were projected beyond the assumed 30 year operational life of the CEER green roof in order to predict a point where each construction phase impact category would be offset. These projected environmental impact break-even points ranged from 7 years for non carcinogenics to 102 years for smog formation potential. Of the assessed environmental impact categories, only the non carcinogenics impact due to construction is projected to be offset within the assumed 30 year operational life of the green roof. These projected construction offset points are summarized in *Table 37*. Calculations can be found in *Appendix N*.

Table 37. Green roof projected construction environmental impact offset

Impact Category	Projected Break-Even Year
Global warming	72
Acidification	59
Carcinogenics	34
Non carcinogenics	7
Respiratory effects	67
Eutrophication	64
Ozone depletion	80
Ecotoxicity	70
Smog	102

5.4 Green roof decommissioning phase

As of the publication of this study (2011), the Villanova University CEER green roof is in the operation phase of its life cycle. It is assumed that the need for decommissioning or refurbishment of the green roof would be due to degradation of the undying drainage liner. For this study, it is assumed that the decommissioning of the CEER green roof would consist of the removal and disposal of all green roof components. Replacement of the green roof system is beyond the defined system boundary of this life cycle assessment. LCI for this scenario is described in the following section.

5.4.1 Green roof component disposal scenario

The CEER green roof disposal decommissioning scenario assumes the disposal of all green roof components. This includes the green roof media and all construction materials. LCI for this decommissioning scenario includes SimaPro’s Ecoinvent Database process for waste disposal and landfill of municipal waste in the U.S. This database process is based on data from U.S. EPA data (PRé Consultants, 2010).

The assumption was made that decommissioning of the green roof is accomplished in one 8-hour work day by a team of 4 laborers, with 4 hours of foreman supervision. Unit costs for labor were estimated based upon general contractor unit cost applied for the bio-retention rain garden construction (N. Abbonizio Contractors, Inc., 2001). Labor unit costs were adjusted for inflation and estimated in terms of 2006 USD (US Inflation Calculator, 2011). The results of this analysis are shown in *Table 38*.

Table 38. Green roof decommissioning phase labor impact

Labor	Quantity	Units	Unit Cost (2006 USD)	Direct Labor Cost (2006 USD)
Laborers	32	hrs	$47.80	$1,530
Foreman	4	hrs	$62.64	$251
Total	36	hrs	-	$1,780

It was also assume that the telescopic boom material handler used for construction was used for decommissioning as well. The assumption was made that operation of a material handler is similar to that of a skid-steer loading. As for the green roof construction, the skid-loader LCI processes was applied to the green roof decommissioning inventory using an estimated material volume of 97 cubic yards. This volume is based on the volume of green roof media and stone which both were moved to the roof during construction by the telescopic boom material handler. Hauling costs for material removal from the site were not included in this analysis.

5.4.2 Decommissioning phase LCIA

TRACI impact categories are applied to assess the environmental impacts of the CEER green roof decommissioning phase scenarios. SimaPro 7.2 software was used to calculate and compile these TRACI impact categories. Social and economic impact categories were calculated without the use of LCA software. *Table 39* summarizes the green roof component disposal decommissioning phase scenario. Impacts are also shown in terms of the LCA functional unit of *impact per acre of impervious drainage area (DA)*.

Table 39. Green roof decommissioning phase impacts

Impact Category	Unit	Green Roof Impact	Impact per Acre Impervious DA
Global warming	kg CO2 eq	1,929	161,593
Acidification	H+ moles eq	66	5,543
Carcinogenics	kg benzen eq	599.75	50,241.00
Non carcinogenics	kg toluen eq	19,404,515	1,625,501,295
Respiratory effects	kg PM2.5 eq	0.21	17.90
Eutrophication	kg N eq	23.98	2,008.95
Ozone depletion	kg CFC-11 eq	0.000018	0.001487
Ecotoxicity	kg 2,4-D eq	144,853	12,134,184
Smog	g NOx eq	1.42	118.70
Onsite labor	hrs	36	3,016
Cost	2006 USD	1,780	149,109

5.5 Green roof complete LCIA

To assess the complete life cycle impact of the Villanova University CEER green roof, the results from each life cycle phase were combined for analysis. *Table 40* summarizes complete life cycle impacts for the green roof. Detailed total green roof life cycle impact calculations can be found in *Appendix O*.

Table 40. Green roof total life cycle impact

Impact Category	Unit	Total LCA Impact	Impact per Acre Imp. DA
Global warming	kg CO2 eq	6,359	532,684
Acidification	H+ moles eq	769	64,459
Carcinogenics	kg benzen eq	603	50,546
Non carcinogenics	kg toluen eq	18,669,129	1,563,898,576
Respiratory effects	kg PM2.5 eq	4.86	407.45
Eutrophication	kg N eq	34.53	2,892.81
Ozone depletion	kg CFC-11 eq	0.000255	0.021366
Ecotoxicity	kg 2,4-D eq	161,685	13,544,225
Smog	g NOx eq	11.86	993.70
Onsite labor	hrs	174	14,576
Cost	2006 USD	49,847	4,175,607

Unlike the rain garden, the CEER green roof provides a net negative impact for all TRACI environmental impact categories. Chapter 6 provides additional interpretation and analysis of the green roof life cycle assessment.

CHAPTER 6: LCA INTERPRETATION AND DISCUSSION

6.1 Interpretation and comparison methodology

The life cycle interpretation phase of a LCA study examines and interprets the results of LCI and LCIA phases. This chapter looks at the outcome of both the rain garden LCA and the green roof LCA, and goes on to makes comparisons between these two green infrastructure practices. For each green infrastructure practice LCA, the construction phase, operation phase, and decommissioning phase impact are examined to identify significant impacts and the potential for improvement in environmental performance throughout the practice life cycle. Comparisons between practices are made based on *impact per impervious drainage area*, which is the functional unit of the study. For comparison, all life cycle costs were adjusted for inflation and are in terms of 2011 USD (US Inflation Calculator, 2011).

6.2 Construction phase interpretation

6.2.1 Rain garden

The Villanova University bio-retention rain garden construction phase is described in Section 4.2 of this paper. Total construction phase impacts are summarized in Section 4.2.6 and in *Table 7*. For the interpretation of these results, impacts attributed to specific materials and processes were examined. A detailed summary of these impacts is shown in *Appendix P*. *Figure 23* graphically summarizes the contribution of all construction materials and processes with regard to the TRACI environmental impact categories. A value of 100% equates to the total construction impact for each impact category.

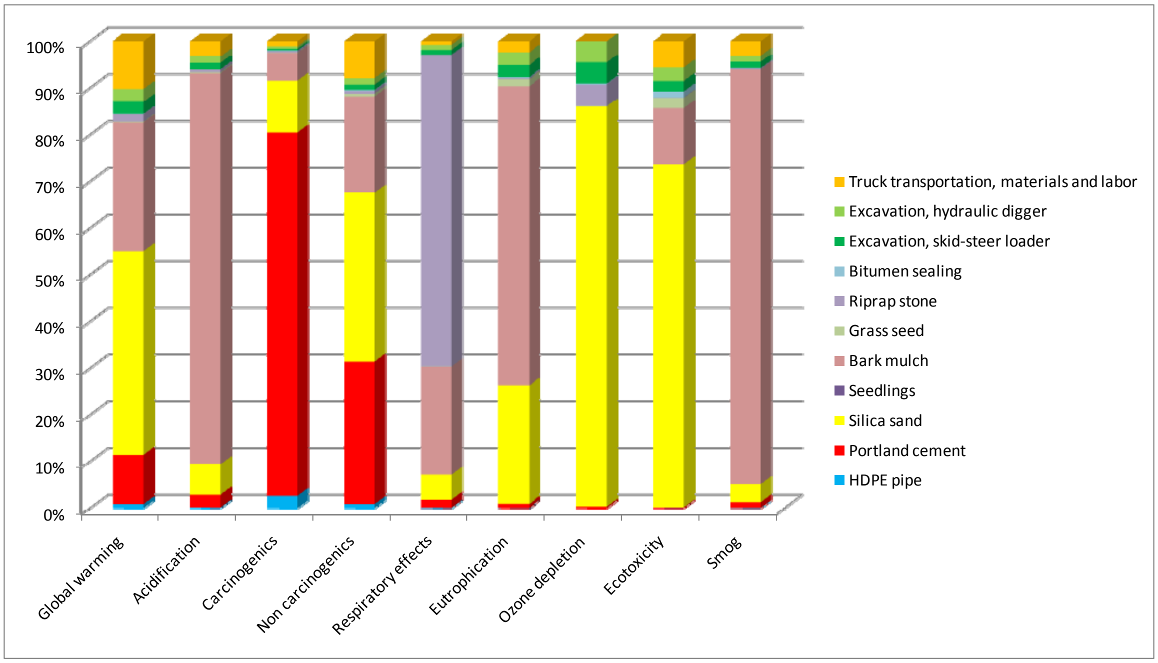

Figure 23. Bio-retention rain garden construction phase impact exploration

Silica sand and bark mulch were identified as the significant environmental impact pathways for the rain garden. The use of silica sand as a soil amendment to produce the rain garden media was identified as the most significant construction impact with regard to four of the nine TRACI impact categories. These environmental impact categories include global warming potential, non carcinogenics, ozone depletion potential, and ecotoxicity. Silica sand also contributes significantly to eurtrophication potential. The use of bark mulch to establish vegetation was identified as the most significant construction impact related to acidification potential and smog. Bark mulch also has a significant contribution to global warming potential, non carcinogenics, and respiratory effects. Other significant impacts for the rain construction phase include the use of Portland cement with regard to carcinogenics and non carcinogenics, and the rain garden plantings with regard to potential respiratory effects. While transportation and onsite construction activities do contribute to the overall construction environmental impact, their contributions pale in comparison to those of the production of the rain garden construction materials.

6.2.2 Green roof

Section 5.2 of this paper describes the CEER green roof construction phase. Total construction phase impacts are summarized in Section 5.2.6 and in *Table 28*. Like the rain garden, impacts attributed to specific materials and processes were examined for interpretation. A detailed summary of these impacts is shown in *Appendix Q*. *Figure 24* graphically summarizes the contribution of all construction materials and processes for the TRACI environmental impact categories. A value of 100% equates to the total construction impact for each impact category.

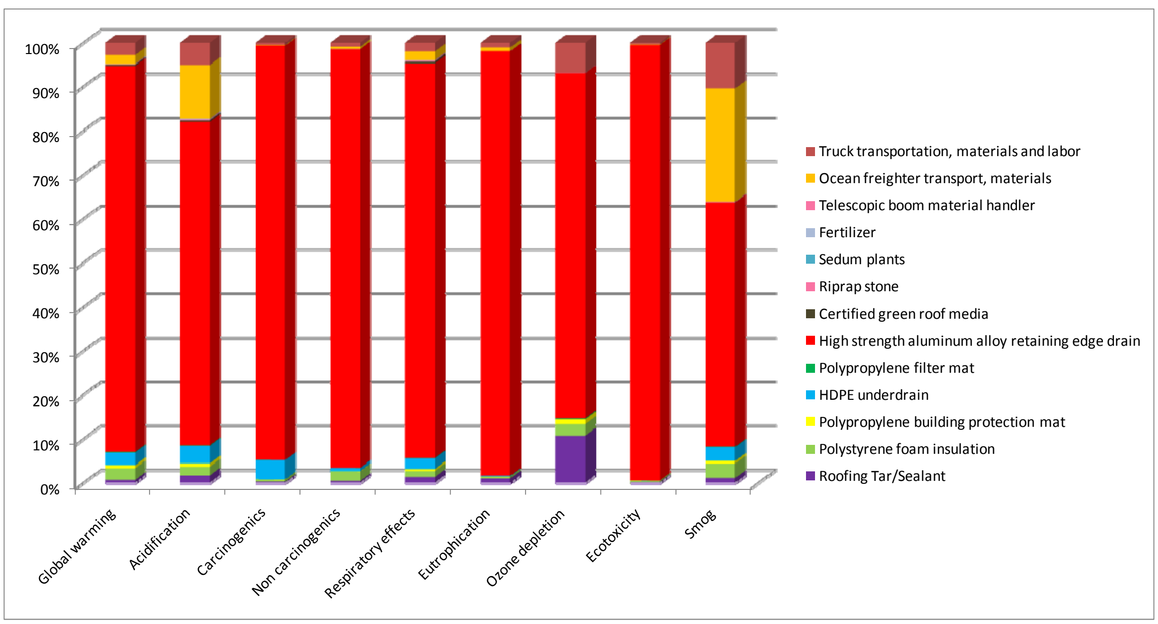

Figure 24. Green roof construction phase impact exploration

The use of a high strength aluminum alloy retaining edge drain was identified as the most significant construction environmental impact. This is consistent across all TRACI impact categories. Transportation of construction materials, specifically by transporation by ocean freighter of the Optigreen green roof components, was seen to have a significant impact on acidification potential and smog formation potential. Other construction material and processes have relatively minimal environmental impact when compared with the high strength aluminum alloy retaining edge drain.

6.2.3 Rain garden verses green roof construction phase impacts

Construction phase impacts were compared between the bio-retention rain garden and the green roof. The comparison between green infrastructure practices was made based on impact per acre of impervious drainage area. This comparison could represent a hypothetical one acre building roof in which two equivalent green infrastructure practices, a 0.2 acre rain garden and a one acre green roof, are being considered for a stormwater retrofit project. *Table 41* summarizes these comparisons. *Figure 25* is a graphical representation of the relative construction impacts of the green infrastructure practices. For comparison purposes, 100% represents the estimated total construction impact of a one acre green roof.

Table 41. Rain garden vs. green roof construction phase impacts per acre impervious DA

Impact category	Units	Rain Garden	Green Roof
Global warming	kg CO2 eq	9,884	636,932
Acidification	H+ moles eq	10,219	120,156
Carcinogenics	kg benzen eq	31	3,068
Non carcinogenics	kg toluen eq	87,883	17,070,597
Respiratory effects	kg PM2.5 eq	51	713
Eutrophication	kg N eq	14	1,681
Ozone depletion	kg CFC-11 eq	0.0007	0.032
Ecotoxicity	kg 2,4-D eq	3,419	2,472,982
Smog	g NOx eq	226	1,240
Onsite labor	hrs	472	8,042
Cost	2011 USD	80,224	4,182,867

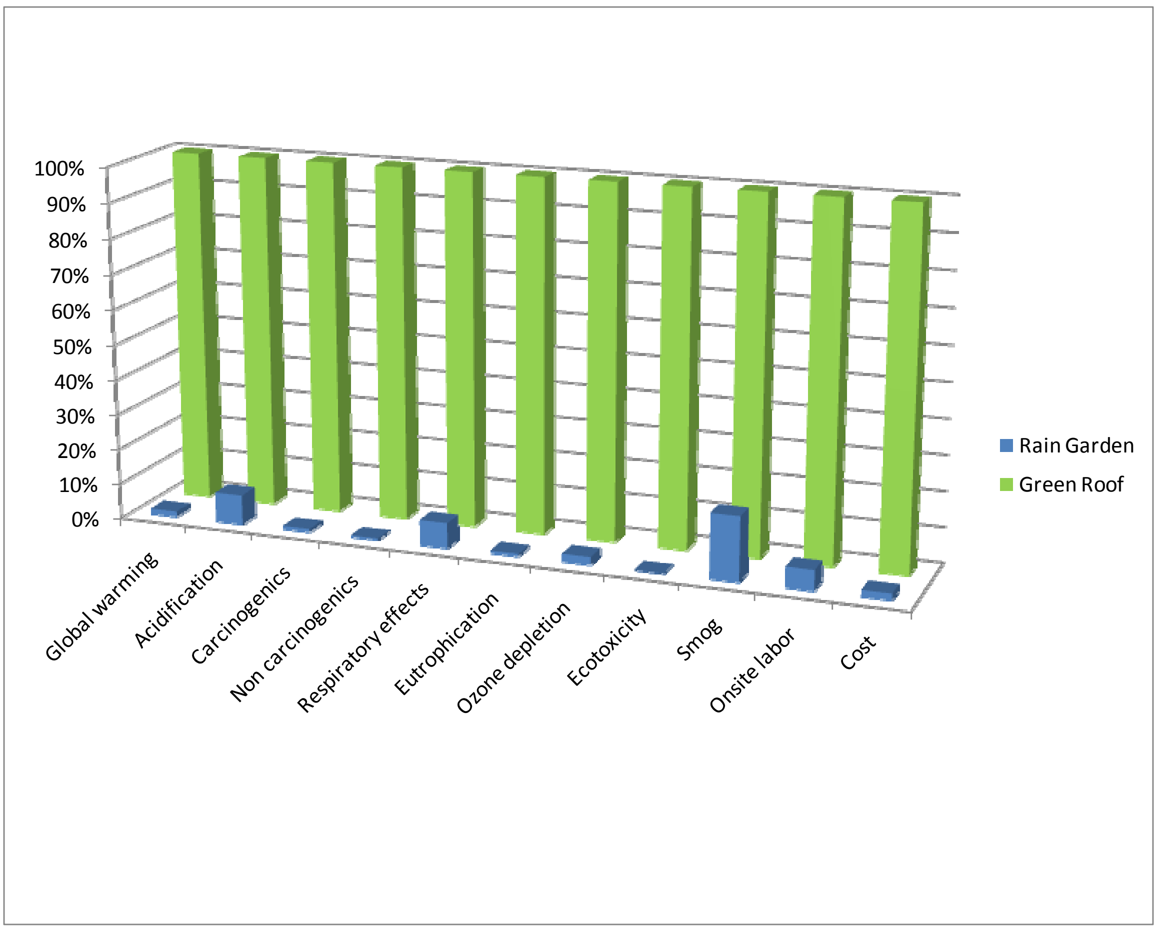

Figure 25. Rain garden vs. green roof construction phase relative impact

This comparison shows that the impacts associated with the construction of a green roof to manage one acre of impervious roof area are of a much larger magnitude than the construction impacts associated with the construction of a rain garden sized to manage that same one acre roof area. The estimated rain garden construction impacts are 1% or less than those of the green roof construction with respect to carcinogenics, non carcinogenics, eutrophication potential, and ecotoxicity. These results are not completely unexpected as a green roof is constructed of a number of manufactured components, while a rain garden is typically constructed using more natural construction materials.

6.3 Operation phase interpretation

6.3.1 Rain garden

The bio-retention rain garden operation phase is described in Section 4.3 of this paper. Total operational phase impacts over an assumed 30 year operational life are summarized in Section 4.3.5 and in *Table 14*. Operational phase analysis shows that the rain garden is a resilient green infrastructure practice that functions with minimal maintenance. This results in minimal negative environmental impacts and minimal life cycle operational costs. Urban forest benefits, stormwater management benefits, and benefits to combined sewer systems were found to net an annual avoided environmental impact over the operational phase of the rain garden. Offset of rain garden construction environmental impacts occur within the operational life of the rain garden for five out of the nine TRACI impact categories.

The calculated urban forest benefit of an annual avoided global warming potential of 1,943 kilograms of carbon dioxide equivalent is enough to offset the operation of one passenger car for approximately four and half months. The added avoided global warming potential for the rain garden in a combined sewer system (232 kg CO2 eq) slightly increases this passenger car operation offset to five months (US EPA, 2011). Additional urban forest benefits such as the creation of wildlife habitat were not considered as well. Stormwater management benefits of rain gardens have been well documented. Because assessed environmental impact categories in this study were limited to those defined by TRACI, the benefits to health of downstream freshwater bodies were not completely quantified. For a combined sewer system, only the environmental impacts of reduced energy use at the wastewater treatment plant were quantified. Other benefits that were not quantified include the avoided maintenance and costs related to the reduced burden on both the conveyance infrastructure and at the downstream wastewater treatment plant, and the impact of the wastewater treatment plant effluent verses the impact of infiltrated runoff. The aesthetic benefits over the operational life of the rain garden were also not considered in this analysis. Although these aesthetic benefits are recognized, methods for quantification are not fully developed.

6.3.2 Green roof

Section 5.3 of this paper describes the CEER green roof operational phase. Total operational phase impacts for an assumed 30 year operational life are summarized in Section 5.3.6 and in *Table 36*. Like the rain garden, the green roof was found to net an annual avoided operational phase environmental impact. Annual maintenance for the green roof was shown to have significantly less environmental impacts than maintenance associated with a traditional roof. Despite these benefits, offsets of the green roof construction environmental impacts are only offset for one out of the nine TRACI impact categories within the operational life of the practice. Some acknowledged benefits over the operational life of the green roof that were not quantified include creation of wildlife habitat, reduction in noise pollution, and aesthetic benefits. Aesthetic benefits have the potential to be significant due to the green roof location in view of a well traveled stairway in the CEER building. This green roof has also been used in various promotional materials for Villanova University. These are all operational phase benefits that are recognized yet difficult to quantify.

6.3.3 Rain garden verses green roof operation phase impacts

Comparisons were made between the operation phase impacts of the bio-retention rain garden and the green roof. Like the construction phase, this comparison is based on impact per acre of impervious drainage area. *Table 42* summarizes these comparisons. Negative values represent avoided environmental impacts. *Figure 26* is a graphical representation of the relative operational impacts of the green infrastructure practices. In this figure 100% represents the estimated total avoided operational impact, with the exceptions of onsite labor and cost, of a one acre green roof.

Table 42. Rain garden vs. green roof operation phase impacts per acre impervious DA

Impact category	Units	Rain Garden	Green Roof
Global warming	kg CO2 eq	-126,608	-265,842
Acidification	H+ moles eq	-4,953	-61,239
Carcinogenics	kg benzen eq	-33	-2,763
Non carcinogenics	kg toluen eq	-225,580	-78,673,315
Respiratory effects	kg PM2.5 eq	-26	-324
Eutrophication	kg N eq	-158	-798
Ozone depletion	kg CFC-11 eq	-0.0004	-0.012
Ecotoxicity	kg 2,4-D eq	-40,308	-1,062,942
Smog	g NOx eq	-27	-365
Onsite labor	hrs	120	3,518
Cost	2011 USD	3,214	325,413

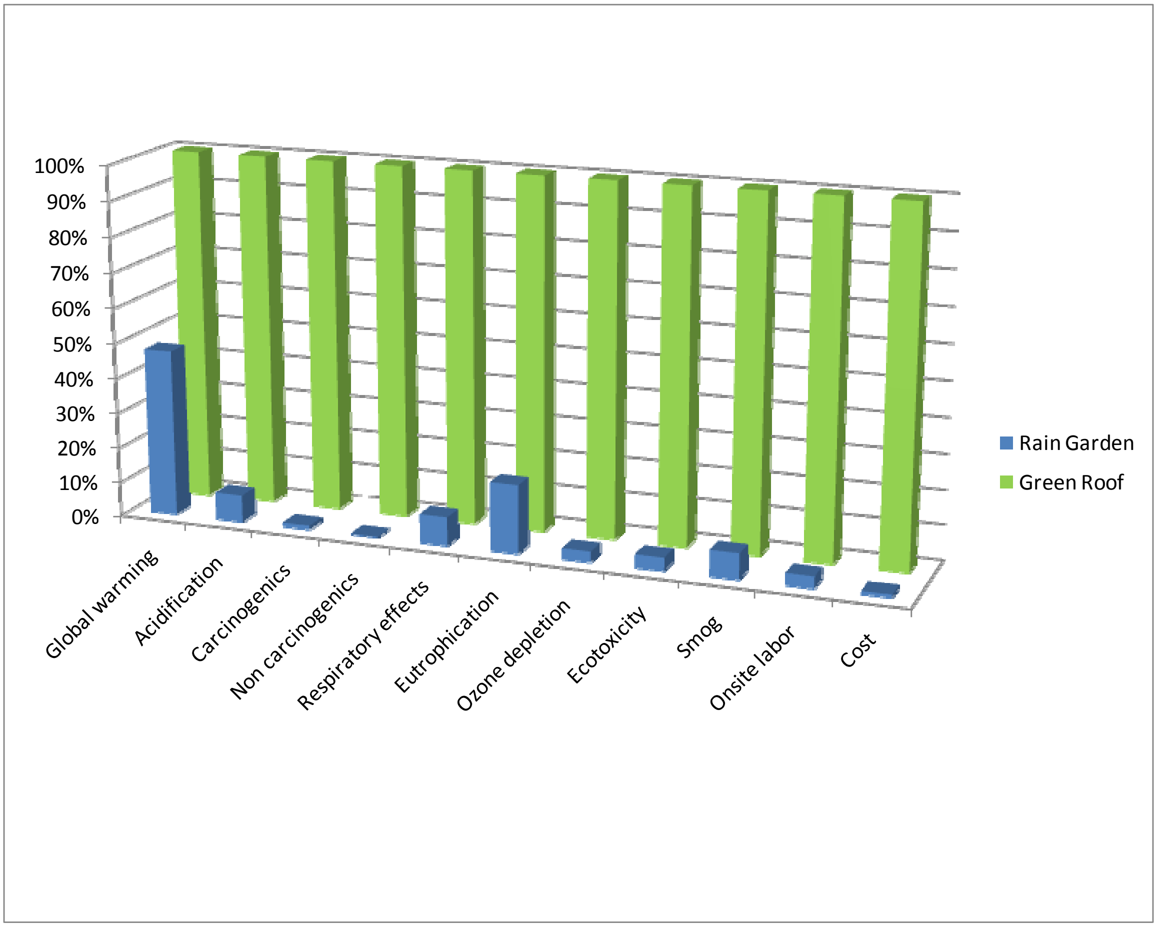

Figure 26. Rain garden vs. green roof operation phase relative impact

This comparison shows that the operational benefits associated with a green roof are greater than the operational benefits of a rain garden sized for the same stormwater management volume reduction goals. These impacts are closer than those seen for the construction phase comparison. The benefits to global warming potential of the rain garden are almost half of the benefits of the equivalent green roof. If these comparisons were made based on the footprint of the green infrastructure practice and not the impervious drainage area, the avoided global potential of the rain garden would be approximately 2.4 times greater than that of the green roof. This is due to the robust vegetation and trees planted in the rain garden. If these green infrastructure comparisons were made based on operational costs rather than impervious drainage area, the rain garden would have superior operational performance in all environmental impact categories with the exception of non carcinogenics. In terms of operational cost, the rain garden would provide approximately 48 times the avoided global warming potential per dollar spent than the green roof.

6.4 Decommissioning phase interpretation

6.4.1 Rain garden

The bio-retention rain garden decommissioning phase is described in Section 4.4 of this paper. Two decommissioning scenarios were explored. Section 4.4.1 summarizes the rain garden media reuse scenario and Section 4.4.2 summarizes the rain garden media disposal scenario. The resulting impact of both of these scenarios is shown in Section 4.4.3. These decommissioning scenarios yield vastly different environmental impacts. *Figure 27* is a graphical representation of the relative decommissioning impacts of the rain garden media reuse scenario and the media disposal scenario. For comparison purposes, 100% represents the estimated total decommissioning impact of rain garden media disposal scenario.

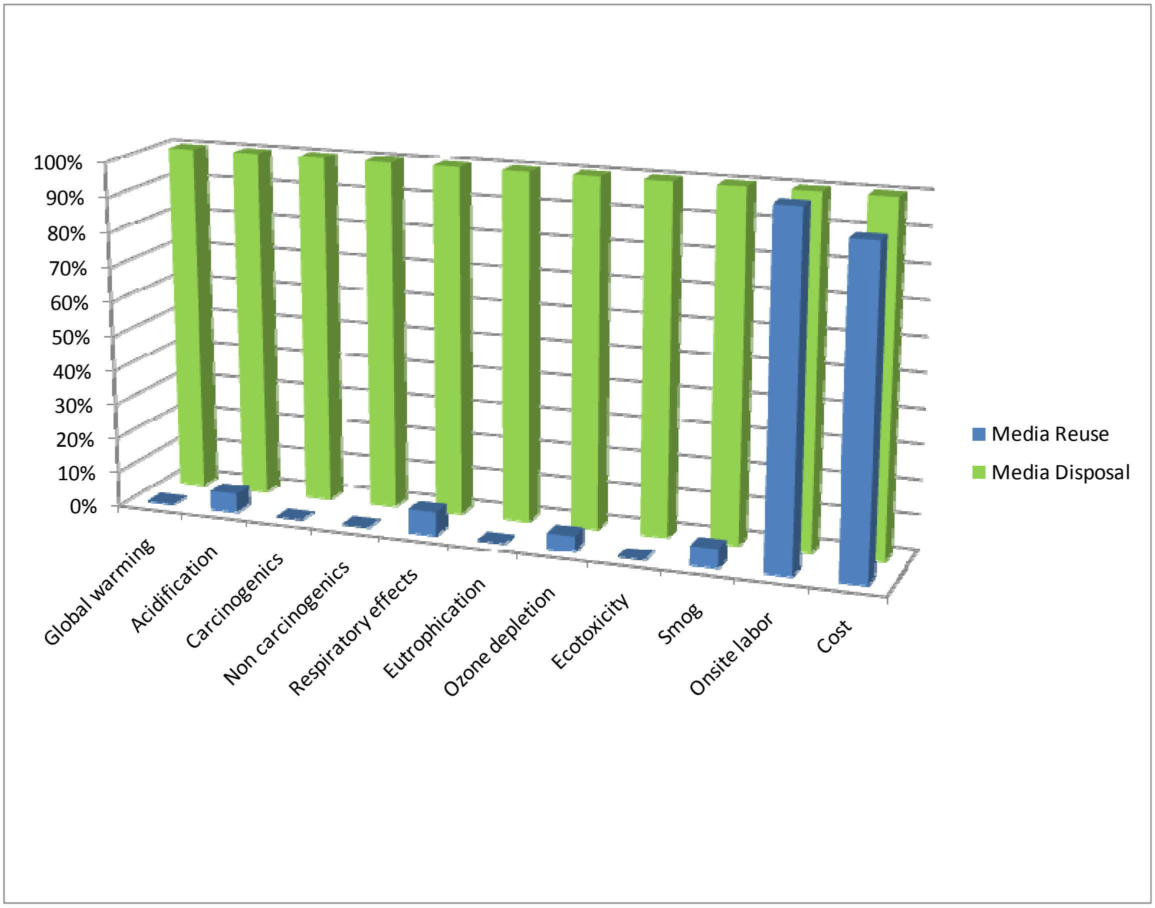

Figure 27. Rain garden decommissioning scenario relative impact

While onsite labor impacts and costs are similar between both decommissioning scenarios, the environmental impacts differ significantly. The media disposal scenario results in dramatically increased environmental impacts than the media reuse scenario. These results indicate a considerable environmental benefit to preventing the rain garden media from going to a landfill. Not considered in this analysis was the monetary value of the rain garden media for use as construction fill material. This addition to the analysis could further support the already strong case for the rain garden media reuse decommissioning scenario.

6.4.2 Green roof

The CEER green roof decommissioning phase is described in Section 5.4. Only one decommissioning scenario was explored for this green infrastructure practice. This scenario assumes the disposal of all green roof components. Section 5.4.2 and *Table 39* summarize the calculated impacts of this decommissioning scenario. While the reuse of the green roof media is unlikely, there may be potential for the recycling of some manufactured green roof components. These potential recycling opportunities were not fully explored for this study.

6.4.3 Rain garden verses green roof decommissioning phase impacts

Decommission phase impacts were compared between both bio-retention rain garden decommissioning scenarios and the green roof. These comparisons were made based on the functional unit of impact per acre of impervious drainage area. *Table 43* summarizes these comparisons. *Figure 28* is a graphical representation of the relative decommissioning impacts. For comparison purposes, 100% represents the estimated total decommissioning impact of a one acre green roof.

Table 43. Rain garden vs. green roof decommissioning phase impacts per ac imperv. DA

Impact category	Units	Rain Garden - Reuse	Rain Garden - Disposal	Green Roof
Global warming	kg CO2 eq	269	102,581	161,593
Acidification	H+ moles eq	144	2,680	5,543
Carcinogenics	kg benzen eq	0.14	34,455	50,241
Non carcinogenics	kg toluen eq	1,104	1,114,626,364	1,625,501,295
Respiratory effects	kg PM2.5 eq	0.55	8	18
Eutrophication	kg N eq	0.37	1,264	2,009
Ozone depletion	kg CFC-11 eq	0.0000	0.0008	0.001
Ecotoxicity	kg 2,4-D eq	88	8,317,209	12,134,184
Smog	g NOx eq	3	57	119
Onsite labor	hrs	80	80	3,016
Cost	2011 USD	14,140	15,288	166,950

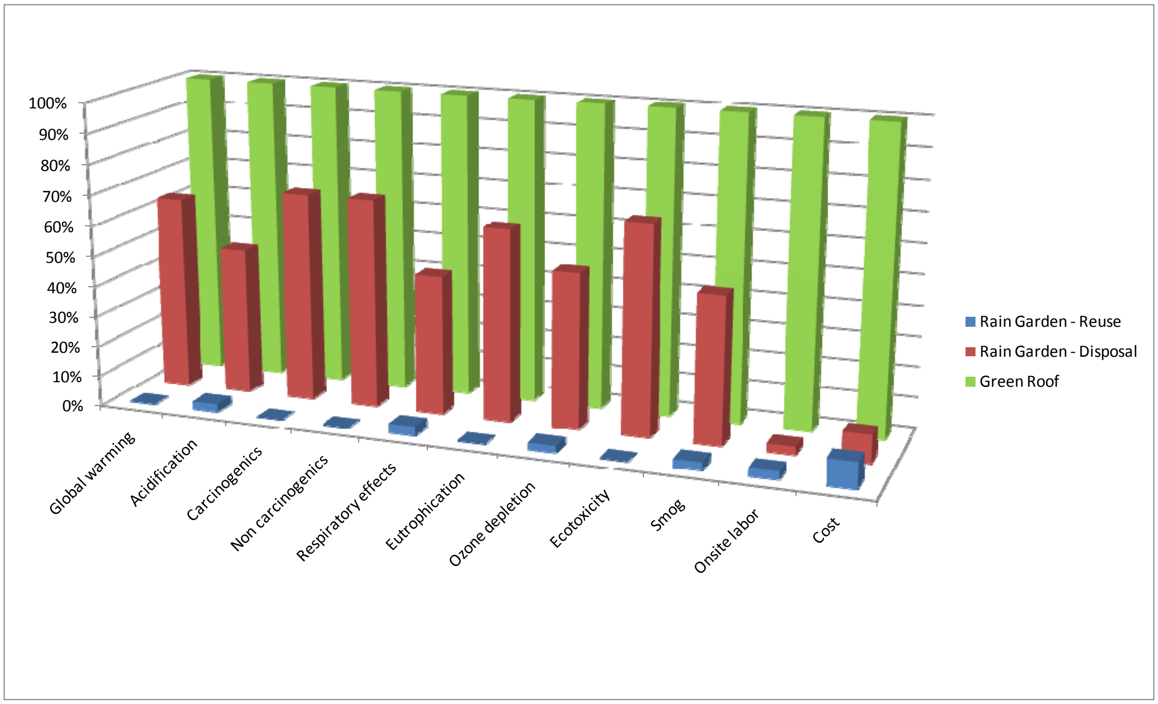

Figure 28. Rain garden vs. green roof decommissioning phase relative impact

These comparisons shows that the decommissioning impacts of the green roof are greater than impacts of the rain garden media disposal scenario and significantly greater than those of the rain garden media reuse scenario. If these comparisons were made based on the footprint of the green infrastructure practice and not the impervious drainage area, the environmental impacts of rain garden media disposal scenario would be from around 2.5 to 3.5 times greater across the TRACI impact categories than those of the green roof. If these green infrastructure comparisons were made based on decommissioning costs rather than impervious drainage area, the rain garden media disposal scenario would have an impact approximately 5 to 8 times greater per dollar spent across the environmental impact categories.

6.5 Compete life cycle interpretation

6.5.1 Rain garden

The bio-retention rain garden complete LCIA is described in Section 4.5 of this paper. As detailed previously, under the media reuse decommissioning scenario, the rain garden provides net avoided environmental impacts for global warming potential, carcinogenics, non carcinogenics, eutrophication potential, and ecotoxicity. The media disposal scenario offsets all environmental benefits accrued over the operation phase of the rain garden, with the exception of global warming potential. For the interpretation of the rain garden complete life cycle, the media reuse decommissioning scenario was explored. *Table 44* summarizes the rain garden total life cycle impact and the impact contribution from each life cycle phase. *Figure 29* is a graphic representation of the relative contribution of each phase of the rain garden life cycle. All these comparisons are made relative to the rain garden construction phase, where 100% represents the total construction phase impact for each impact category.

Table 44. Rain garden complete life cycle impact summary (media reuse)

Impact Category	Unit	Construction Phase	Operation Phase	Decomissioning Phase	Total LCA Impact	Impact per Acre Imp. DA
Global warming	kg CO2 eq	4,942	-63,304	134	-58,228	-116,456
Acidification	H+ moles eq	5,109	-2,476	72	2,705	5,411
Carcinogenics	kg benzen eq	15	-16.69	0.07	-1.26	-2.51
Non carcinogenics	kg toluen eq	43,941	-112,790	552	-68,297	-136,594
Respiratory effects	kg PM2.5 eq	26	-13.14	0.27	12.82	25.64
Eutrophication	kg N eq	7	-78.90	0.18	-71.92	-143.84
Ozone depletion	kg CFC-11 eq	0.0004	-0.000185	0.000016	0.000192	0.000383
Ecotoxicity	kg 2,4-D eq	1,709	-20,154	44	-18,401	-36,801
Smog	g NOx eq	113	-13.43	1.56	101.06	202.12
Onsite labor	hrs	236	60	40	336	672
Cost	2001 USD	31,454	1,260	5,544	38,258	76,516

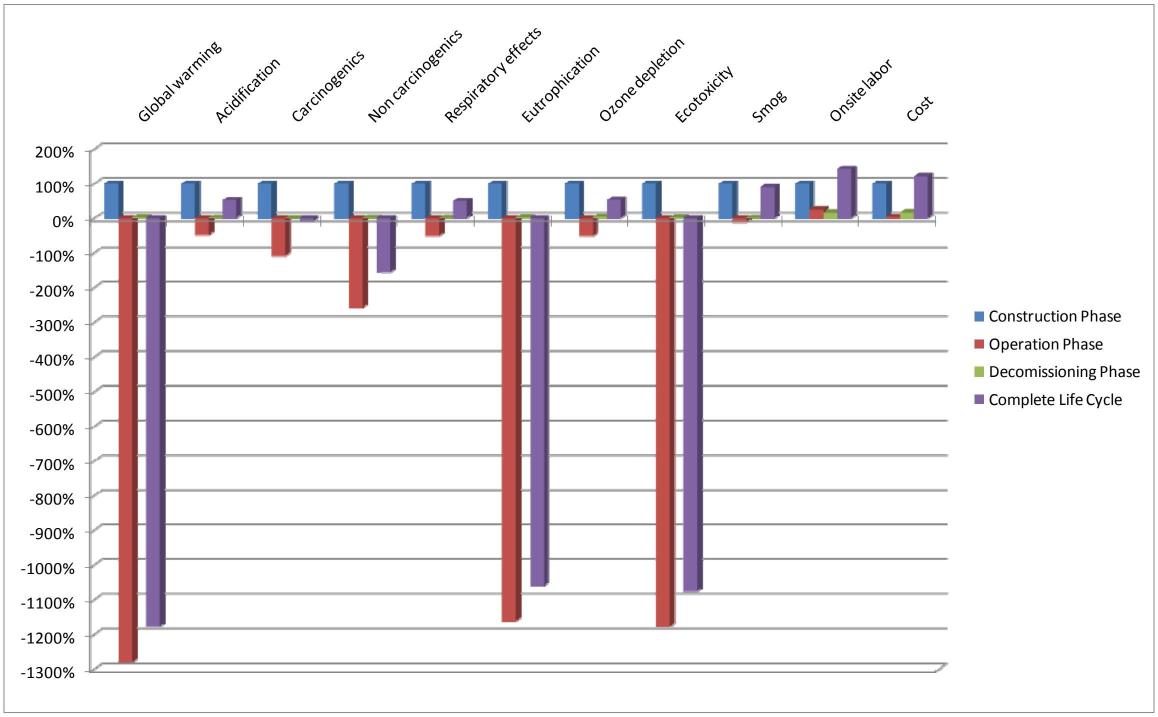

Figure 29. Rain garden complete life cycle impact exploration (media reuse)

From this analysis, it is shown that the construction phase is the major contributing life cycle phase to all adverse environmental impacts, as well as the total life cycle cost and labor impacts. The operation phase provides significant avoided environmental impacts relative to the construction phase impacts. These operation phase avoided impacts are in excess of 11 times the construction impacts with regard to global warming potential, eutrophication potential, and ecotoxicity. Decommissioning phase impacts for the rain garden media reuse scenario were identified as insignificant relative to the rain garden construction phase impacts.

6.5.2 Green roof

The CEER green roof complete LCIA is described in Section 5.5. Unlike, the rain garden, the green roof complete life cycle was found to have an adverse impact for all TRACI environmental impact categories. *Table 45* summarizes the green roof total life cycle impact and the impact contribution from each life cycle phase. *Figure 30* is a graphic representation of the relative contribution of each phase of the green roof life cycle. All comparisons are made relative to the green roof construction phase, where 100% represents the total construction phase impact for each impact category.

Table 45. Green roof complete life cycle impact summary

Impact Category	Unit	Construction Phase	Operation Phase	Decomissioning Phase	Total LCA Impact	Impact per Acre Imp. DA
Global warming	kg CO2 eq	7,603	-3,174	1,929	6,359	532,684
Acidification	H+ moles eq	1,434	-731	66	769	64,459
Carcinogenics	kg benzen eq	37	-33	600	603	50,546
Non carcinogenics	kg toluen eq	203,781	-939,167	19,404,515	18,669,129	1,563,898,576
Respiratory effects	kg PM2.5 eq	8.52	-3.87	0.21	4.86	407.45
Eutrophication	kg N eq	20.07	-9.52	23.98	34.53	2,892.81
Ozone depletion	kg CFC-11 eq	0.000380	-0.000143	0.000018	0.000255	0.021366
Ecotoxicity	kg 2,4-D eq	29,521	-12,689	144,853	161,685	13,544,225
Smog	g NOx eq	14.81	-4.36	1.42	11.86	993.70
Onsite labor	hrs	96	42	36	174	14,576
Cost	2006 USD	44,597	3,470	1,780	49,847	4,175,607

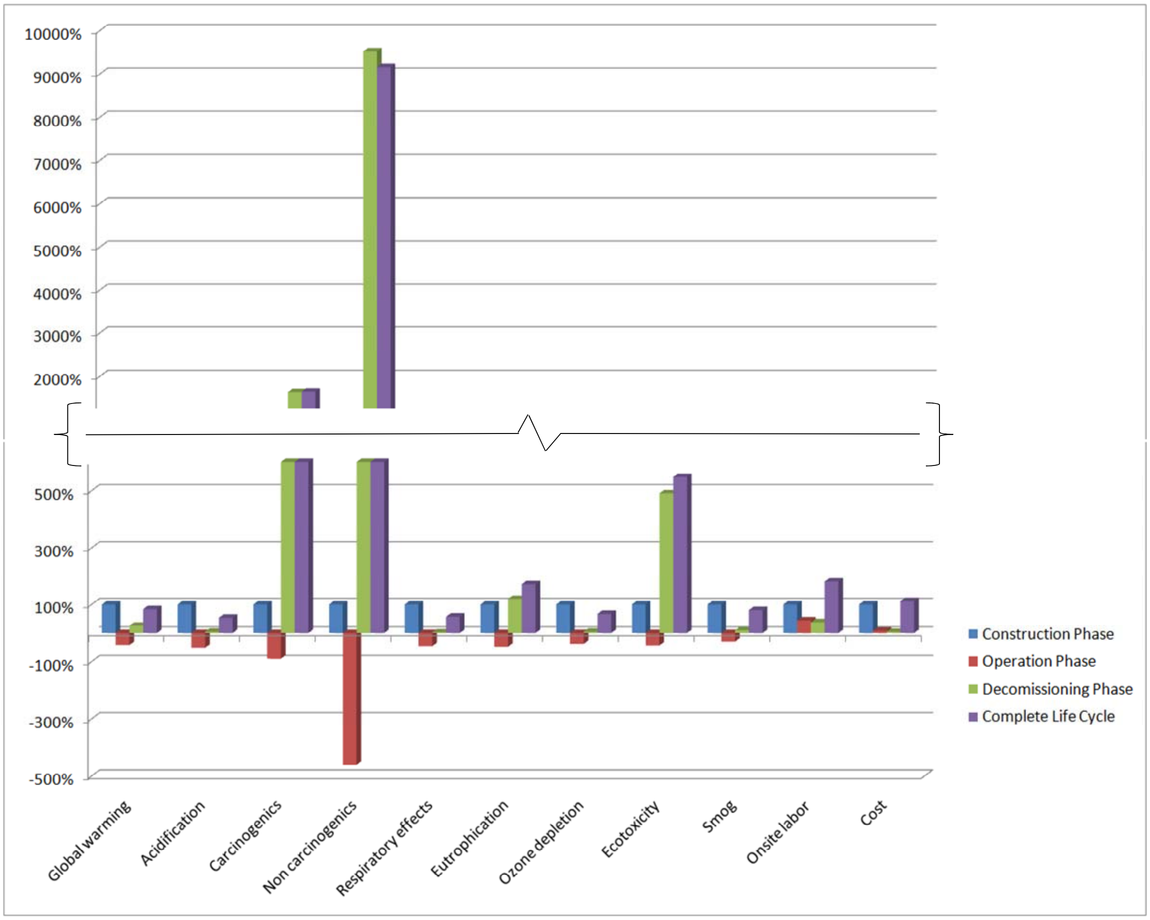

Figure 30. Green roof complete life cycle impact exploration

This analysis shows that the construction phase is the major contributing life cycle phase for adverse environmental impacts with regard to global warming potential, acidification potential, respiratory effects, ozone depletion potential, and smog formation potential. As expected, the construction phase is also the major influence on total life cycle cost and labor impacts. For the carcinogenics, non carcinogenics, eutrophication potential, and excotoxicity impact categories, the decommissioning phase was found to be the main contributing phase. These decommissioning phase impacts are more than 15 times the construction impacts with regard to carcinogenics, and in excess of 90 times the construction impacts for non carcinogenics. For all environmental impact categories, the avoided impacts accrued over the life cycle of the green roof are offset by the combined impacts of the construction phase and the decommissioning phase.

6.5.3 Rain garden verses green roof complete life cycle impacts

Complete life cycle impacts were compared between the bio-retention rain garden and the CEER green roof. For the comparison, the rain garden complete life cycle with the media reuse decommissioning scenario was used. Comparisons between green infrastructure practices were made based on the functional unit of impact per acre of impervious drainage area. *Table 46* summarizes these comparisons. Negative values represent avoided environmental impacts. *Figure 28* is a graphical representation of the relative complete life cycle impacts. In this figure, 100% represents the estimated total life cycle impact of a one acre green roof.

Table 46. Rain garden vs. green roof complete life cycle impacts per ac imperv. DA

Impact category	Units	Rain Garden	Green Roof
Global warming	kg CO2 eq	-116,456	532,684
Acidification	H+ moles eq	5,411	64,459
Carcinogenics	kg benzen eq	-2.51	50,546
Non carcinogenics	kg toluen eq	-136,594	1,563,898,576
Respiratory effects	kg PM2.5 eq	26	407
Eutrophication	kg N eq	-144	2,893
Ozone depletion	kg CFC-11 eq	0.0004	0.021
Ecotoxicity	kg 2,4-D eq	-36,801	13,544,225
Smog	g NOx eq	202	994
Onsite labor	hrs	672	14,576
Cost	2011 USD	97,578	4,675,230

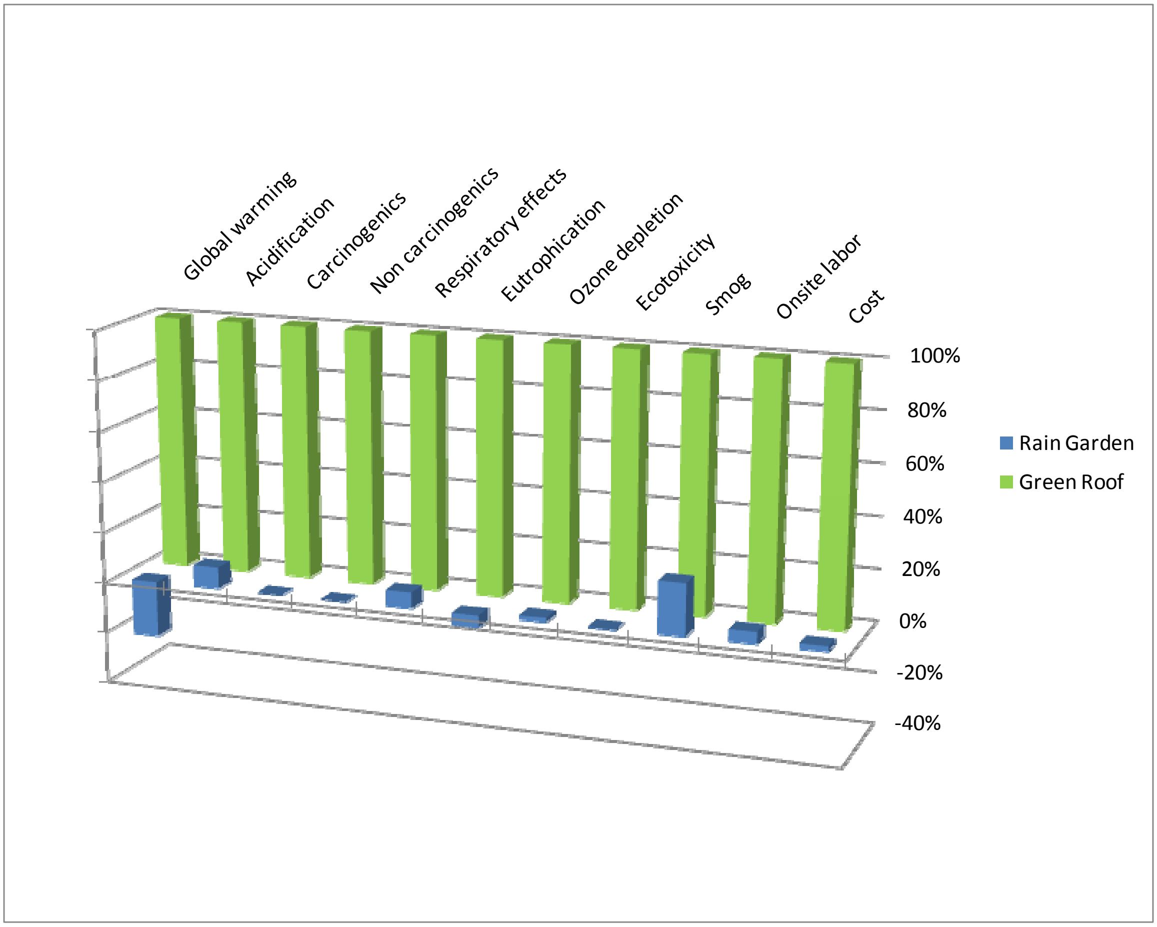

Figure 31. Rain garden vs. green roof complete life cycle relative impact

This analysis shows that while the rain garden provides avoided environmental impacts for five out of nine TRACI impact categories, the green roof results in adverse environmental impacts across all categories. Adverse environmental impacts that do result from the rain garden life cycle are of a much smaller magnitude of those resulting from the life cycle of a green roof sized for similar stormwater management performance. This was also observed with regard to life cycle cost and onsite labor impact.

Overall, the rain garden life cycle provides superior environmental and economic performance. One factor not considered is the availability and value of the area needed to construct a rain garden. This is a significant factor in urban areas. An advantage that the green roof has in this regard is that a building roof area may be considered unused space. Another factor not considered when comparing these green infrastructure practices is the aesthetic impacts. The CEER green roof clearly has superior aesthetic value than the bio-retention rain garden, yet metrics to quantify these aesthetic impacts are not straightforward and were beyond the scope of this study.

CHAPTER 7: RECOMMENDATIONS AND CONCLUSIONS

7.1 Rain garden recommendations

Evaluation of the Villanova University bio-retention rain garden using life cycle assessment allows for the identification of pathways toward improved green infrastructure practice environmental performance. In the previous chapter of this paper, the construction phase of the rain garden was found to result in the greatest environmental impact on the rain garden life cycle. With the knowledge gained from this analysis, it is possible to redesign future rain gardens to reduce environmental impacts. Silica sand and bark mulch were identified as the significant impact pathways for the rain garden construction phase.

The use of silica sand as a construction material carries with it the environmental impacts accrued through the energy intensive mining and refining processes needed for its production. It is recommended that alternatives be investigated to the use of silica sand as a soil amendment to produce rain garden media. An alternative could be to use the natural soil as rain garden media and to accept a lower infiltration rate. This could require a larger rain garden footprint to achieve the same stormwater management performance. Another alternative design is to replace the silica sand with another material such as naturally occurring sand, a sandy soil, or an engineered rain garden media. Another alternative could be to reduce the volume of silica sand by reducing the depth of the rain garden media.

When analyzed using life cycle analysis, bark mulch is linked to the environmental impacts associated with the logging industry. The use of bark mulch to establish vegetation is accepted and cost effective practice. One alternative could be to use a natural compost material from a local source in place of bark mulch. If bark mulch must be used it is recommended that it is only applied for the initial establishment of the rain garden vegetation and not reapplied throughout the operation phase of the practice. Any design alternatives for silica sand, bark mulch, or any other materials and processes should be evaluated using the same life cycle assessment methodology. Only then can alternative designs be property assessed and compared for both cost and environmental impacts. It may be found that some alternatives simply will shift adverse impacts to other impact areas.

It is recommended that a decommissioning plan be put in place for the Villanova University bio-retention rain garden that requires the reuse of the rain garden media at the end of the practice life cycle. This media could potentially be used as fill material for other construction project on the Villanova University Campus. The disposal of this material in a landfill was projected to have environmental consequences that offset most of the environmental benefits accrued over the operational life of the rain garden. Maintenance plans and decommissioning plans should be addressed at the design stage of all rain gardens. It is recommended that these maintenance and decommissioning plans promote the reuse of the rain garden media.

To further assess and expand on the life cycle impact of a rain garden, alternative land uses could be examined using the same life cycle assessment methodology. For the Villanova University bio-retention rain garden this may include a traditionally landscaped traffic island or a turf area. These vegetated alternatives will also have urban forest benefits. A turf area may be a good baseline to use for future rain garden benefit analysis. For example, the carbon storage and sequestration achieved by turf would be subtracted from the predicted benefits of the rain garden vegetation. On the other hand, a maintained turf area will require more maintenance, such as routine mowing, than a rain garden. So these avoided maintenance impacts would then also have to be considered in the rain garden life cycle assessment. As the boundaries of a life cycle assessment study expand, the complexity of the analysis may grow exponentially. These alternative land use aspects were beyond the system boundaries of this rain garden life cycle assessment but are recommended to be investigated in future rain garden studies.

7.2 Green roof recommendations

The CEER green roof life cycle assessment showed that both the construction phase and the decommissioning phase have considerable environmental impacts relative to the green roof life cycle. For the green roof construction phase, the use of a high strength aluminum alloy retaining edge drain was identified as the most significant environmental impact. It is recommended that alternative edge drain designs and alternative edge drain materials be investigated. These alternative designs should be evaluated using same life cycle assessment methodology. The replacement of this single component could dramatically change the overall green roof life cycle impacts and thus the conclusions of this comparative study.

Transportation by ocean freighter of the green roof components used for construction was found to have a significant impact on acidification potential and smog formation potential. These components were manufactured in Germany therefore the impacts associated with their transportation are unavoidable. To reduce these impacts, it is recommended that the designers of future green roofs pursue green roof components that are manufactured domestically or even locally. This may require slight or even dramatic variations to the original green roof design. These design variations would also need to be evaluated using life cycle assessment in order to make educated comparisons of environmental impacts. For example, changes in media depth will result in changes to the building energy benefits of the green roof. The green roof life cycle assessment methodology developed for this study allows for the analysis of these complex relationships.

The decommissioning phase of the CEER green roof was found to be the main contributing life cycle phase for many of the assessed environmental impact categories. This is based on the assumption that all green roof components are sent to a landfill for disposal. It is recommended that a decommissioning plan be put in place for the CEER green roof that promotes the reuse or recycling of as many green roof components as possible. Many of the green roof components such as the drainage layer and filter fabric are made from recyclable materials. It is important that these materials are recognized and appropriately sorted at the time of decommissioning. Proper management of the green roof decommissioning phase will play an important role in the overall environmental performance of this green infrastructure practice.

Social impacts that include aesthetic benefits, of the CEER green roof were not quantified in this study. Being visible from the main stairway of the CEER building on the Villanova University Campus, the aesthetics of this green roof can be enjoyed by as many as hundreds of students and university employees on any given day of the school year. Photographs of the CEER green roof have also been used in numerous Villanova University promotional materials. These social benefits are recognized as considerable, yet they are difficult to quantify. While beyond the scope of this study, it is recommended that future studies dedicate additional focus to the assessment of these green roof social impacts.

7.3 Green infrastructure life cycle assessment methodology and tools

The green infrastructure life cycle assessment methodology established for this study follows methodology set forth for LCA by the International Standards Organization (ISO) under the ISO 14000 environmental management standards. While this methodology was originally established for the LCA of products, the high level framework of these standards was observed in this study as a highly effect approach for the LCA of green infrastructure practices. The more specific green infrastructure LCA methodology developed for this study and the applicability of utilized green infrastructure LCI tool are discussed in the following sections.

7.3.1 Green infrastructure LCA methodology

A life cycle assessment methodology specific for green infrastructure practices was developed for this study using the ISO 14000 environmental management standards as a framework. The functional unit used to make direct comparisons between practices was *Impervious Drainage Area,* basis based on sizing guidelines detailed in the *PA BMP Manual* (PADEP, 2006). These sizing guidelines are recommendations that may not be appropriate for all green infrastructure retrofit project. For comparison between practices, values are linearly interpolated from the calculated impacts. Linear interpolation up to an acre may not be appropriate because of the relatively small size the actual green infrastructure practices, specifically the CEER green roof. While it may be appropriate to linearly scale some impacts like those resulting from material quantities, other impacts such as cost and labor may become more efficient with increased scale. It recommended that further green infrastructure practices with a range of scales are studied to assess the accuracy of impact scaling.

Other functional units such as cost and practice footprint were briefly examined in this study. These functional units yielded significantly different results. Green infrastructure is typically implemented in order to meet a regulatory need. Therefore comparisons made on a regulatory basis will be the most useful to planning and design professionals. While volume reduction may not always be the primary project goal for the implementation of green infrastructure, these goals are set forth by regulatory criteria and for that reason were used the basis of comparisons in this study. It is recommended that other function units for comparison be explored in more detail.

For green infrastructure operation phase analysis, impacts and benefits were annualized and projected linearly over the life cycle of a practice. It is recognized that even with proper maintenance, practice performance may degrade over time. This degradation in performance will vary between green infrastructure practice types and even vary between individual practices of the same type. Continued monitoring and study of these practices is recommended to better understand and thus better predict the long term performance of green infrastructure.

For this study, data collection methods for LCI included engineering plans, contractor invoices, onsite inspections, interviews with professionals involved in the design and construction, the analysis of photographic records, analysis of stormwater management monitoring data and the review of published literature. The green infrastructure practices on the Villanova University Campus have been continuous studied and monitored which provides for great availability of data and records for this assessment. As this type of analysis is intended to be applied at the planning phase of projects, it is recommended that further studies be undertaken for actual retrofit project in their early planning stages. It is envisioned that LCI data of these studies would rely more heavily on conceptual engineering plans and planting plans and on published data such as that presented in this study.

7.3.2 United States Life Cycle Inventory Database

Data from the U.S. LCI Database was applied when possible throughout this study. This database was found to contain robust LCI dataset for transportation processes and basic construction materials. European LCI databases, such as the Ecoinvent Database (PRé Consultants, 2010) and the European Life Cycle Database (ELCD), were identified as having a more extensive library of LCI inputs for materials and processes. An information gap identified in all LCI databases used in this study is the availability of LCI processes associated with heavy construction activities. Currently, these processes are limited to the excavation processes in the Ecoinvent Database (PRé Consultants, 2010). While more LCI data for the operation of construction equipment may exist in privately owned and licensed LCI databases, these resources were not available for this study. It is recommended that with increasing interest in LCA of infrastructure practices, the addition of construction processes to the U.S. LCI Database become a priority of the National Renewable Energy Laboratory (NREL).

7.3.3 SimaPro 7.2

SimaPro 7.2, by PRé Consultants, was identified in this study as a powerful and valuable process flow modeling tool for green infrastructure LCA. The built-in databases provide an efficient means of searching and identifying applicable LCI processes. This software was found to be most valuable as a tool for the accounting of energy and materials flows and the calculation of inventory results to the TRACI impact categories used for this study (PRé Consultants, 2010). It is recommended that proprietary LCA software, such as SimaPro 7.2, be utilized for all future green infrastructure LCA studies.

7.3.4 i-Tree Eco

For this study the i-Tree Eco model was used to assess the urban forest benefits of the bio-retention rain garden. A limitation of this model is that it only has the ability to calculate carbon storage and sequestration for trees (US Forest Service, 2010). The bio-retention rain garden has extensive shrub cover, therefore the carbon storage and sequestration benefits of this rain garden are most likely underestimated. Because the CEER green roof is an extensive green roof without tree cover, the i-Tree Eco model was not applied to assess this green infrastructure practice. While this model is currently an applicable and useful tool for green infrastructure LCA, it has even greater potential if future versions are expanded to include more detailed analysis of shrub, grass, and turf areas.

7.4 Future work

Evaluation and comparison of green infrastructure practices using life cycle assessment is a difficult undertaking. This study is a first attempt to establish and test a methodology for assessing these complex systems. From the results of this study, the need for greatly expanded research in this area has been identified. The following recommendations are for future work both at Villanova University and throughout the research community at large.

1. LCA of additional types of structural green infrastructure practices. At Villanova University this includes pervious pavement sites, subsurface infiltration practices, and constructed wetland systems.
2. LCA of nonstructural green infrastructure practices such as open space preservation, riparian buffer restoration, and stream restoration.
3. LCA of green infrastructure practices of different scales to investigate the applicability of impact scaling techniques utilized in this study.
4. Explore other functional units for comparison of green infrastructure practices.
5. Investigate impact assessment methodology beyond the TRACI impact categories, including weighted single impact scoring techniques.
6. Expand on social and economic impact categories and metrics for green infrastructure practices.
7. Detailed impact assessment of design alternatives for individual green infrastructure practices.
8. LCA of green infrastructure practices at conceptual design stages to investigate the usefulness of the green infrastructure LCA methodology outlined by this study as a tool for project planning.
9. Application of the green infrastructure LCA methodology established in this study to a broader array of infrastructure projects.

7.5 Conclusions

While life cycle assessment is an established technique for the analysis of environmental impacts of products, LCA of infrastructure practices is a relatively undeveloped area of study. This study is a first attempt to develop and test a LCA methodology specific to green infrastructure practices. The results from the analysis of green infrastructure practices at Villanova University show considerable differences in the environmental performance of different practice types. These results also reveal previously unrecognized construction, operation, and decommissioning components that have significant influence on the environmental, economic, and social performance of green infrastructure practices. With an improved understanding of these impact pathways, professionals have the ability to investigate alternative green infrastructure designs to address a wider range of sustainability goals beyond stormwater management, and across the entire life cycle of a project. It is envisioned that future infrastructure project goals and associated regulatory guidelines will encompass this holistic and multidisciplinary approach. In this future, life cycle assessment is a powerful tool toward sustainable and restorative planning and design.

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APPENDIX A: RAIN GARDEN CONSTRUCTION DOCUMENTS

A.1 General Contractor invoice

N. Abbonizio Contractors, Inc.
1250 Conshohocken Road
Conshohocken, PA 19428
(610)275-8540

Invoice 2034.0000

09/24/2001

02232412
Villanova University
800 Lancaster Avenue
Villanova, PA

2100.26
Villanova - Bio-Retention Basin

Villanova, PA

Your Order No: [ ]   Our Work Orders: [ ]

Contractor supplied the following labor, equipment and material necessary to construct a bioretention system according to plans including all excavation, disposal of soil, connection to existing inlet, installation of 12" pipe, removal of a section of curb, placement of a one foot deep layer of sand, placement of a four feet deep layer of select soil, and grading and placement of two feet of grass sod buffer:

Line	Description	Qty	Unit	Price	Amount
1.00	Thursday August 2nd				
2.00	1 Laborer for 8 Hours @ $42.00 per Hour	8.00	Hrs	42.0000	336.00
3.00	Foreman Supervision for 4 Hours @ $55.00 Hour	4.00	Hrs	55.0000	220.00
4.00	Backhoe for 8 Hours @ $85.00 per Hour	8.00	Hrs	85.0000	680.00
5.00	Friday August 3rd				
6.00	1 Laborer for 8 Hours @ $42.00 per Hour	8.00	Hrs	42.0000	336.00
7.00	Foreman Supervision for 4 Hours @ $55.00 per Hour	4.00	Hrs	55.0000	220.00
8.00	490 John Deere Excavator for 8 Hours @ $125.00 per Hour	8.00	Hrs	125.0000	1,000.00
9.00	Triaxle for 8 Hours @ $62.50 per Hour	8.00	Hrs	62.5000	500.00
10.00	Monday August 6th				
11.00	1 Laborer for 8 Hours @ $42.00 per Hour	8.00	Hrs	42.0000	336.00
12.00	Foreman Supervision for 4 Hours @ $55.00 per Hour	4.00	Hrs	55.0000	220.00
13.00	490 John Deere Excavator for 8 Hours @ $125.00 per Hour	8.00	Hrs	125.0000	1,000.00
14.00	Triaxle for 8 Hours @ $62.50 per Hour	8.00	Hrs	62.5000	500.00

N. Abbonizio Contractors, Inc.
1250 Conshohocken Road
Conshohocken, PA 19428
(610)275-8540

Invoice 2034.0000

09/24/2001

02232412
Villanova University
800 Lancaster Avenue
Villanova, PA

2100.26
Villanova - Bio-Retention Basin

Villanova, PA

Your Order No:

Our Work Orders:

14.00	Triaxle for 8 Hours @ $62.50 per Hour	8.00	Hrs	62.5000	500.00
15.00	6 Loads hauled out to dump @ $75.00 per Load	6.00	Loads	75.0000	450.00
16.00	Tuesday August 7th				
17.00	2 Laborers for 8 Hours Each @ $42.00 per Hour Each	16.00	Hrs	42.0000	672.00
18.00	Foreman Supervision for 4 Hours @ $55.00 per Hour	4.00	Hrs	55.0000	220.00
19.00	Triaxle for 8 Hours @ $62.50 per Hour	8.00	Hrs	62.5000	500.00
20.00	Saw for 1/2 Day @ $60.00 per Day	0.50	Day	60.0000	30.00
21.00	Wednesday August 8th				
22.00	3 Laborers for 8 Hours each @ $42.00 per Hour Each	24.00	Hrs	42.0000	1,008.00
23.00	Foreman Supervision for 4 Hours @ $55.00 per Hour	4.00	Hrs	55.0000	220.00
24.00	Shredder for 8 Hours @ $150.00 per Hour	8.00	Hrs	150.0000	1,200.00
25.00	Backhoe for 12 Hours @ $85.00 per Hour	12.00	Hrs	85.0000	1,020.00
26.00	Small Dump Truck for 8 Hours @ 52.00 per Hour	8.00	Hrs	52.0000	416.00
27.00	6 Loads hauled out to dump @ $75.00 per Load	6.00	Loads	75.0000	450.00
28.00	Triaxle for 8 Hours @ $62.50 per Hour	8.00	Hrs	62.5000	500.00
29.00	Thursday August 9th				

N. Abbonizio Contractors, Inc.
1250 Conshohocken Road
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02232412
Villanova University
800 Lancaster Avenue
Villanova, PA

2100.26
Villanova - Bio-Retention Basin

Villanova, PA

Your Order No:

Our Work Orders:

30.00	2 Laborers for 8 Hours each @ $42.00 per Hour Each	16.00	Hrs	42.0000	672.00
31.00	Foreman Supervision for 4 Hours @ $55.00 per Hour	4.00	Hrs	55.0000	220.00
32.00	Backhoe for 8 Hours @ $85.00 per Hour	8.00	Hrs	85.0000	680.00
33.00	Kawaski Loader for 8 Hours @ $110.00 per Hour	8.00	Hrs	110.0000	880.00
34.00	Shredder for 8 Hours @ $150.00 per Hour	8.00	Hrs	150.0000	1,200.00
35.00	Friday August 10th				
36.00	3 Laborers for 8 Hours Each @ $42.00 per Hour Each	24.00	Hrs	42.0000	1,008.00
37.00	Foreman Supervision for 4 Hours @ $55.00 per Hour	4.00	Hrs	55.0000	220.00
38.00	Loader for 8 Hours @ $110.00 per Hour	8.00	Hrs	110.0000	880.00
39.00	490 John Deere Excavator for 8 Hours @ $125.00 per Hour	8.00	Hrs	125.0000	1,000.00
40.00	Small Dump Truck for 8 Hours @ 52.00 per Hour	8.00	Hrs	52.0000	416.00
41.00	Backhoe for 4 Hours @ $85.00 per Hour	4.00	Hrs	85.0000	340.00
42.00	Monday August 13th				
43.00	2 Laborers for 8 Hours Each @ $42.00 per Hour	16.00	Hrs	42.0000	672.00
44.00	Foreman Supervision for 4 Hours @ $55.00 per Hour	4.00	Hrs	55.0000	220.00
45.00	490 John Deere Excavator for 8 Hours @ $125.00 per Hour	8.00	Hrs	125.0000	1,000.00

N. Abbonizio Contractors, Inc.
1250 Conshohocken Road
Conshohocken, PA 19428
(610)275-8540

Invoice 2034.0000

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02232412
Villanova University
800 Lancaster Avenue
Villanova, PA

2100.26
Villanova - Bio-Retention Basin

Villanova, PA

Your Order No:

Our Work Orders:

46.00	Loader for 8 Hours @ $110.00 per Hour	8.00	Hrs	110.0000	880.00
47.00	Tuesday August 14th				
48.00	1 Laborer for 8 Hours @ $42.00 per Hour	8.00	Hrs	42.0000	336.00
49.00	Foreman Supervision for 4 Hours @ $55.00 per Hour	4.00	Hrs	55.0000	220.00
50.00	Loader for 8 Hours @ $110.00 per Hour	8.00	Hrs	110.0000	
51.00	490 John Deere Excavator for 8 Hours @ $125.00 per Hour	8.00	Hrs	125.0000	1,000.00
52.00	Wednesday August 15th				
53.00	2 Laborers for 8 Hours Each @ $42.00 per Hour	16.00	Hrs	42.0000	672.00
54.00	Foreman Supervision for 4 Hours @ $55.00 per Hour	4.00	Hrs	55.0000	220.00
55.00	Loader for 8 Hours @ $110.00 per Hour	8.00	Hrs	110.0000	880.00
56.00	Backhoe for 8 Hours @ 85.00 per Hour	8.00	Hrs	85.0000	680.00
57.00	Thursday August 16th				
58.00	Ford Tractor with York Rake for 8 Hours @ $60.00 per Hour	8.00	Hrs	60.0000	480.00
59.00	Friday August 17th				
60.00	3 Laborers for 2 Hours Each @ $42.00 per Hour	6.00	Hrs	42.0000	252.00
61.00	Thursday August 23rd				

N. Abbonizio Contractors, Inc.
1250 Conshohocken Road
Conshohocken, PA 19428
(610)275-8540

Invoice 2034.0000

09/24/2001

02232412
Villanova University
800 Lancaster Avenue
Villanova, PA

2100.26
Villanova - Bio-Retention Basin

Villanova, PA

Your Order No:

Our Work Orders:

62.00	2 Laborers for 1 Hour Each @ $42.00 per Hour Each	2.00	Hrs	42.0000	84.00
63.00	Roller for 1 Hour @ $50.00 per Hour	1.00	Hrs	50.0000	50.00
64.00	Saturday August 25th				
65.00	2 Laborers for 2 Hours Each @ $42.00 per Hour Each	4.00	Hrs	42.0000	168.00
66.00	Materials				2,755.00

Amount Due This Invoice **$30,119.00**

A.2 Nursery invoice

Octoraro Native Plant Nursery, Inc.
6126 Street Road
Kirkwood, PA 17536
717-529-3160

INVOICE

Villanova University - Grounds Department

Order Number: 1611

SOLD TO:
Villanova University - Grounds Department
800 Lancaster Avenue
Villanova, PA 19085-1699

SHIP TO:
Villanova University - Grounds Department

Request Date:	Invoice Date:	Date Shipped:	Carrier:	Tax Exempt #:	Flag Colors:
09/21/2001	09/24/2001	09/24/2001	Customer Pick-up	75-25069-0	Primary: UNKNOWN
Contact Person:	**Phone Number:**	**Fax:**	**PO Number:**	**Terms:**	Secondary: UNKNOWN
Chuck Leeds	(610) 519-4426	519-6500	Bio-retention Area	Net 30 Days	

Ref	Ordered	Shipped	BO	Description	Size	Price	Extension
0	200	200	0	Ammophilia breviligulata "Cape" American beachgrass	Bare root	0.30	60.00
0	10	10	0	Baccharis halimifolia Groundsel tree	18-24" 1 gal	6.00	60.00
0	10	10	0	Iva frutescens Marsh elder	18-24" 1 gal	6.00	60.00
0	100	100	0	Panicum amarum Coastal panic grass	2" Plug	0.75	75.00
0	100	100	0	Panicum virgatum Switchgrass	2" Plug	0.75	75.00
0	10	10	0	Prunus maritima Beach plum	18-24" 1 gal	6.00	60.00
0	100	100	0	Schizachyrium scoparium Little bluestem	2" Plug	0.95	95.00
0	100	100	0	Solidago sempervirens Seaside goldenrod	2" Plug	0.75	75.00

From date of delivery: 1 1/2% per month,
(18% per year) added to all accounts past due.

Per ______________________________

Claims will receive consideration
only when made within 5 days
after delivery.

SubTotal:	560.00
Tax:	0.00
Freight:	100.00
TOTAL:	**660.00**

APPENDIX B: RAIN GARDEN CONSTRUCTION QUANTITY CALCULATIONS

B.1 Material quantity calculations

[redacted]

B.2 Planting quantity calculations

[redacted]

APPENDIX C: RAIN GARDEN CONSTRUCTION EQUIPMENT OPERATION

[redacted]

APPENDIX D: RAIN GARDEN CONSTRUCTION MATERIAL AND LABOR TRANSPORTATION CALCULATIONS

Materials	Origin/Destination	Date	Vehicle	Distance (km)	Total Payload (lbs)	Total Payload (kg)	Transportation Units (kgkm)	Life Cycle Database Process	Notes and Calculation Assumptions
Silica Sand	Octoraro Native Plant Nursery, Inc. - 6126 Street Road, Kirkwood, PA 17536, 717-529-3160	?	Dump Truck	25.9	225800	102421.2	2652708	US: Transport, combination truck, average fuel mix	Assume delivery from local quarry
Stone	Octoraro Native Plant Nursery, Inc. - 6126 Street Road, Kirkwood, PA 17536, 717-529-3160	?	Dump Truck	25.9	12300	5579.2	144501	US: Transport, combination truck, average fuel mix	Assume delivery from local quarry
Excavated material	N. Abbonizio Contractors, Inc. - 1250 Conshohocken Road, Conshohocken, PA 19428 - 610-275-8540	?	Dump Truck	13.7	395289	179300.1	2456411	US: Transport, combination truck, average fuel mix	164 cy removed. Average Porosity = 0.46, Calculated Bulk Density = 1.43 g/cm3
Cement	N. Abbonizio Contractors, Inc. - 1250 Conshohocken Road, Conshohocken, PA 19428 - 610-275-8540	?	Truck	13.7	838	379.9	5205	US: Transport, single unit truck, gasoline powered	Assume delivery by general contractor
Asphalt	N. Abbonizio Contractors, Inc. - 1250 Conshohocken Road, Conshohocken, PA 19428 - 610-275-8540	?	Truck	13.7	4	2.0	27	US: Transport, single unit truck, gasoline powered	Assume delivery by general contractor
Grass seed	N. Abbonizio Contractors, Inc. - 1250 Conshohocken Road, Conshohocken, PA 19428 - 610-275-8540	?	Truck	13.7	9	4.3	59	US: Transport, single unit truck, gasoline powered	Assume delivery by general contractor
Mulch	N. Abbonizio Contractors, Inc. - 1250 Conshohocken Road, Conshohocken, PA 19428 - 610-275-8540	?	Truck	13.7	5220	2367.8	32438	US: Transport, single unit truck, gasoline powered	Assume delivery by general contractor
Seedlings	N. Abbonizio Contractors, Inc. - 1250 Conshohocken Road, Conshohocken, PA 19428 - 610-275-8540	9/24/2007	Truck	85.6	540	244.9	20967	US: Transport, single unit truck, gasoline powered	Assume 3 lbs per seedling
Laborers	N. Abbonizio Contractors, Inc. - 1250 Conshohocken Road, Conshohocken, PA 19428 - 610-275-8540	2001 Aug. 2, 3, 6, 7, 8, 9, 10, 13, 14, 15, 17, 23, 25	Truck	13.7	4810	2181.8	29890	US: Transport, single unit truck, gasoline powered	Assume two laborers weighing 185 lbs each and 13 total trips to the site.
Foreman	N. Abbonizio Contractors, Inc. - 1250 Conshohocken Road, Conshohocken, PA 19428 - 610-275-8540	2001 Aug. 2, 3, 6, 7, 8, 9, 10, 13, 14, 15	Truck	13.7	1665	755.2	10347	US: Transport, single unit truck, gasoline powered	Assume one foreman weighing 185 lbs and 9 total trips to the site.

APPENDIX E: RAIN GARDEN VEGETATION SURVEY AND URBAN FOREST MODEL INPUT

E.1 Input summary

Grid	**All**
Area	360 square meters

	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O
Ground Cover			1.57	4.01				46.30		

						UFORE Species List - **Closest Match**		
	Species	Height (ft)	% Total Area	% Shrub Area	% Missing	**SppCode**	**SpeciesName**	**CommonName**
Shrubs	Mugwort	6.5	14.83	30.80	0	AR20	Artemisia species	sagebrush
	Aster	3.5	10.00	20.77	0	BAHA	Baccharis halimifolia	Eastern baccharis
	Golden Rod	9	1.50	3.12	0	LOCA	Lonicera canadensis	American fly honeysuckle
	Switch Grass	4	13.80	28.66	0	VAVI2	Vaccinium virgatum	Smallflower blueberry
	Box Elder	3	0.13	0.27	0	ACNE	Acer negundo	Boxelder
	Little Blue Stem	5.5	5.63	11.69	0	AG2	Agrostis species	bentgrass
	Smartweed	2	1.25	2.60	0	PO9	Polygonum species	knotweed
	Green Foxtail	5.5	0.63	1.31	0	ALVI5	Alnus viridis	Green alder
	White Snakeroot	1	0.38	0.79	0	AG4	Ageratina species	snakeroot

				Height (ft)			Crown Attributes (ft)			UFORE Species List - **Closest Match**			
Tree ID	Species	DR (deg)	DS (ft)	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing	**SppCode**	**SpeciesName**	**NewSpeciesName**	**CommonName**
T1	Beech Plum	82	28.58	9.5	9.5	2	6	6	10	PRMA2	Prunus maritima		Beach plum
T2	Winterberry	83	30.95	7	7	2	9	5	0	EUBU6	Euonymus bungeanum		Winterberry
T3	Beech Plum	83	33.55	7	7	1	4	4	75	PRMA2	Prunus maritima		Beach plum
T4	Sycamore	245	19.3	7.5	7.5	2	3	3	0	PL3	Platanus species		sycamore
T5	Winterberry	230	10.68	8.5	8.5	2	4	4	40	EUBU6	Euonymus bungeanum		Winterberry
T6	Black Chokeberry	130	15.13	9	8	2.5	6	10	50	PHME13	Aronia arbutifolia var. nigra	Photinia melanocarpa	Black chokeberry
T7	Groundsel Tree	56	6.75	11	11	3	11	9	40	BAHA	Baccharis halimifolia		Eastern baccharis
T8	Groundsel Tree	76	5.84	6	6	1	4	4	10	BAHA	Baccharis halimifolia		Eastern baccharis
T9	Winterberry	227	3.37	6	6	3	5	6.5	5	EUBU6	Euonymus bungeanum		Winterberry
T10	Winterberry	291	8.93	8	8	2	4	5	25	EUBU6	Euonymus bungeanum		Winterberry

E.2 Survey subplot layout

E.3 Data entry sheets by subplot

Grid	**A1**
Area	9 square meters

	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O
Ground Cover				21				79		

	Species	Height (ft)	% Area	% Missing
Shrubs				

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	**A2**
Area	9 square meters

	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O
Ground Cover				84.8				15.2		

	Species	Height (ft)	% Area	% Missing
Shrubs				

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	**A3**
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O
								100		

Shrubs	Species	Height (ft)	% Area	% Missing

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	**A4**
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O
								100		

Shrubs	Species	Height (ft)	% Area	% Missing

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	**A5**
Area	9 square meters

	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O
Ground Cover								100		

	Species	Height (ft)	% Area	% Missing
Shrubs				

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	**A6**
Area	9 square meters

	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O
Ground Cover								100		

	Species	Height (ft)	% Area	% Missing
Shrubs				

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	**A7**
Area	9 square meters

	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O
Ground Cover								100		

	Species	Height (ft)	% Area	% Missing
Shrubs				

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	**A8**
Area	9 square meters

	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O
Ground Cover			62.8					37.2		

	Species	Height (ft)	% Area	% Missing
Shrubs				

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	B1
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O
				13.4				68.6		

Shrubs	Species	Height (ft)	% Area	% Missing
	Mugwort	6.5	18	0

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	B2
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O

Shrubs	Species	Height (ft)	% Area	% Missing
	Mugwort	6.5	10	0
	Aster	3.5	20	0
	Golden Rod	9	20	0
	Switch Grass	4	25	0
	Box Elder	3	5	0
	Little Blue Stem	5.5	20	0

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	B3
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O

Shrubs	Species	Height (ft)	% Area	% Missing
	Mugwort	6.5	25	0
	Aster	3.5	20	0
	Switch Grass	4	25	0
	Little Blue Stem	5.5	25	0
	Golden Rod	9	5	0

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing
Black Chokeberry	T6	9	8	2.5	6	10	50

Grid	B4
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O

Shrubs	Species	Height (ft)	% Area	% Missing
	Mugwort	6.5	25	0
	Aster	3.5	20	0
	Switch Grass	4	25	0
	Little Blue Stem	5.5	25	0
	Golden Rod	9	5	0

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	B5
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O

Shrubs	Species	Height (ft)	% Area	% Missing
	Mugwort	6.5	5	0
	Aster	3.5	5	0
	Switch Grass	4	40	0
	Little Blue Stem	5.5	40	0
	Golden Rod	9	5	0
	Smartweed	2	5	0

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing
Winterberry	T5	8.5	8.5	2	4	4	40

Grid	B6
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O

Shrubs	Species	Height (ft)	% Area	% Missing
	Mugwort	6.5	15	0
	Aster	3.5	5	0
	Switch Grass	4	40	0
	Little Blue Stem	5.5	40	0

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing
Sycamore	T4	7.5	7.5	2	3	3	0

Grid	B7
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O

Shrubs	Species	Height (ft)	% Area	% Missing
	Mugwort	6.5	60	0
	Switch Grass	4	20	0
	Green Foxtail	5.5	20	0

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	B8
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O
								100		

Shrubs	Species	Height (ft)	% Area	% Missing

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	**C1**
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O
				41				17		

Shrubs	Species	Height (ft)	% Area	% Missing
	Mugwort	6.5	35	0
	Switch Grass	4	7	0

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing
Winterberry	T2	7	7	2	9	5	0
Beech Plum	T3	7	7	1	4	4	75

Grid	**C2**
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O

Shrubs	Species	Height (ft)	% Area	% Missing
	Mugwort	6.5	10	0
	Aster	3.5	30	0
	Switch Grass	4	30	0
	Little Blue Stem	5.5	30	0

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing
Beech Plum	T1	9.5	9.5	2	6	6	10

Grid	**C3**
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O

Shrubs	Species	Height (ft)	% Area	% Missing
	Aster	3.5	45	0
	Switch Grass	4	50	0
	Smartweed	2	5	0

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	C4
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O

Shrubs	Species	Height (ft)	% Area	% Missing
	Aster	3.5	75	0
	Switch Grass	4	25	0

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing
Groundsel Tree	T7	11	11	3	11	9	40
Groundsel Tree	T8	6	6	1	4	4	10

Grid	C5
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O

Shrubs	Species	Height (ft)	% Area	% Missing
	Aster	3.5	10	0
	Switch Grass	4	65	0
	Little Blue Stem	5.5	25	0

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing
Winter Berry	T9	6	6	3	5	6.5	5
Winter Berry	T10	8	8	2	4	5	25

Grid	C6
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O

Shrubs	Species	Height (ft)	% Area	% Missing
	Aster	3.5	30	0
	Switch Grass	4	20	0
	Little Blue Stem	5.5	20	0
	Smartweed	2	30	0

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	C7
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O

Shrubs	Species	Height (ft)	% Area	% Missing
	Mugwort	6.5	40	0
	Switch Grass	4	15	0
	Green Foxtail	5.5	5	0
	Aster	3.5	40	0

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	C8
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O
								100		

Shrubs	Species	Height (ft)	% Area	% Missing

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	D1
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O
								30		

Shrubs	Species	Height (ft)	% Area	% Missing
	Mugwort	6.5	30	0
	Aster	3.5	10	0
	Golden Rod	9	25	0
	White Snakeroot	1	5	0

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	D2
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O

Shrubs	Species	Height (ft)	% Area	% Missing
	Mugwort	6.5	50	0
	Aster	3.5	10	0
	Switch Grass	4	30	0
	White Snakeroot	1	10	0

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	D3
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O

Shrubs	Species	Height (ft)	% Area	% Missing
	Mugwort	6.5	30	0
	Aster	3.5	30	0
	Switch Grass	4	30	0
	Smartweed	2	10	0

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	D4
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O

Shrubs	Species	Height (ft)	% Area	% Missing
	Mugwort	6.5	80	0
	Aster	3.5	20	0

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	D5
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O

Shrubs	Species	Height (ft)	% Area	% Missing
	Mugwort	6.5	30	0
	Aster	3.5	30	0
	Switch Grass	4	40	0

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	D6
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O

Shrubs	Species	Height (ft)	% Area	% Missing
	Mugwort	6.5	60	0
	Switch Grass	4	40	0

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	D7
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O
								5		

Shrubs	Species	Height (ft)	% Area	% Missing
	Mugwort	6.5	70	0
	Switch Grass	4	25	0

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	**D8**
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O
								100		

Shrubs	Species	Height (ft)	% Area	% Missing

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	**E1**
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O
								100		

Shrubs	Species	Height (ft)	% Area	% Missing

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	E2
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O
				84.8				100		

Shrubs	Species	Height (ft)	% Area	% Missing

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	E3
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O
								100		

Shrubs	Species	Height (ft)	% Area	% Missing

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	E4
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O
								100		

Shrubs	Species	Height (ft)	% Area	% Missing

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	E5
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O
								100		

Shrubs	Species	Height (ft)	% Area	% Missing

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	E6
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O
								100		

Shrubs	Species	Height (ft)	% Area	% Missing

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	E7
Area	9 square meters

Ground Cover	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O
								100		

Shrubs	Species	Height (ft)	% Area	% Missing

		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

Grid	**E8**
Area	9 square meters

	%Bldg	%CMNT	%Tar	%Rock	%Soil	%Diff/Mulch	%Herb/Ivy	%Main. Grass	%Unmain. Grass	%H2O
Ground Cover			15					85		

	Species	Height (ft)	% Area	% Missing
Shrubs				

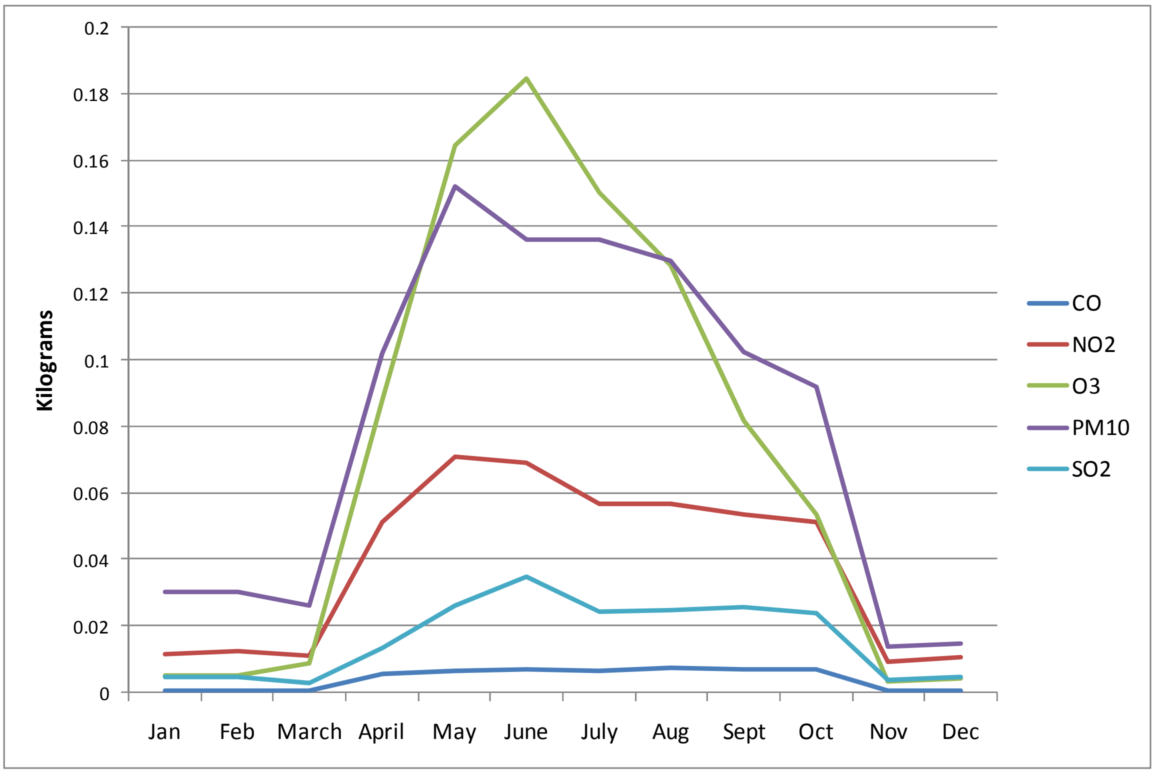
		Height (ft)			Crown Attributes (ft)		
Tree ID	Location	Total Height	Live Top	Crown Base	Width N-S	Width E-W	% Missing

APPENDIX F: RAIN GARDEN URBAN FOREST MODEL RESULTS

F.1 Air pollutant removal

Month	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual Total
CO	0.000567	0.000581	0.000482	0.005915	0.006666	0.007146	0.006637	0.007686	0.007349	0.007227	0.000508	0.000545	0.051309
NO2	0.011559	0.01241	0.011055	0.051441	0.071102	0.069384	0.056815	0.05693	0.053596	0.051375	0.009438	0.010821	0.465926
O3	0.00534	0.005327	0.008722	0.087643	0.164266	0.184518	0.15044	0.128303	0.082125	0.053409	0.003452	0.004508	0.878053
PM10	0.030363	0.030282	0.026094	0.102063	0.152181	0.136221	0.136126	0.129876	0.102217	0.091735	0.013839	0.014638	0.965635
SO2	0.004646	0.004749	0.002939	0.013352	0.026483	0.03507	0.024712	0.024754	0.025686	0.023946	0.003857	0.004912	0.195106

Air Pollutant	Annual Removal by Vegetation	Units
CO	0.05	kg
NO2	0.47	kg
O3	0.88	kg
PM10	0.97	kg
SO2	0.20	kg



F.2 Carbon storage and sequestration

Parameter	Value	Units
Annual Carbon Storage	490	kg C
Annual Carbon Sequestration	40	kg C
Total Avoided Global Warming Potential	1,943	kg CO2 eq

APPENDIX G: RAIN GARDEN STORMWATER MANAGEMENT PERFORMANCE

G.1 Total Suspended Solids (TSS)

Year	Inflow (cf)	Outflow (cf)	Volume Removed (cf)	TSSI (mg/L)	TSSI (kg)	TSSO (mg/L)	TSSO (kg)	TSS Removed (kg)
2003	67,385	26,933	40,453	4.67	8.91	20.00	15.25	-6.35
2004	88,572	52,399	36,173	40.10	100.60	5.10	7.57	93.03
2005	60,610	31,490	29,119	286.14	491.14	5.07	4.52	486.62
2006	90,236	45,194	45,042	148.55	379.62	8.71	11.15	368.48
2007	66,624	31,944	34,680	207.20	390.94	86.75	78.48	312.46
2008	53,022	24,945	28,078	217.85	327.12	44.18	31.21	295.91
2009	87,281	44,783	42,498	746.03	1,844.04	462.97	587.17	1,256.87
2010	70,865	52,111	18,754	299.82	601.70	21.59	31.86	569.84
Average			34,350		518.01		95.90	422.11

G.2 Total Dissolved Solids (TDS)

Year	Inflow (cf)	Outflow (cf)	Volume Removed (cf)	TDSI (mg/L)	TDSI (kg)	TDSO (mg/L)	TDSO (kg)	TDS Removed (kg)
2003	67,385	26,933	40,453	30.47	58.14	68.70	52.40	5.74
2004	88,572	52,399	36,173	86.91	218.01	45.55	67.60	150.41
2005	60,610	31,490	29,119	93.52	160.52	31.07	27.71	132.81
2006	90,236	45,194	45,042	55.15	140.94	50.03	64.04	76.90
2007	66,624	31,944	34,680	284.12	536.07	33.77	30.55	505.51
2008	53,022	24,945	28,078	513.08	770.44	367.38	259.53	510.92
2009	87,281	44,783	42,498	1,581.77	3,909.82	86.65	109.90	3,799.93
2010	70,865	52,111	18,754	548.71	1,101.21	15.66	23.12	1,078.10
Average			34,350		861.89		79.36	782.54

G.3 Total Nitrogen (TN)

Year	Inflow (cf)	Outflow (cf)	Volume Removed (cf)	TNI (mg/L)	TNI (kg)	TNO (mg/L)	TNO (kg)	TNO Removed (kg)
2003	67,385	26,933	40,453	0.05	0.10			
2004	88,572	52,399	36,173	1.15	2.88	0.83	1.24	1.65
2005	60,610	31,490	29,119	1.13	1.93	1.50	1.34	0.59
2006	90,236	45,194	45,042					
2007	66,624	31,944	34,680	2.85	5.37	4.40	3.98	1.39
2008	53,022	24,945	28,078	2.62	3.94	0.82	0.58	3.35
2009	87,281	44,783	42,498					
2010	70,865	52,111	18,754					
Average			34,350		2.84		1.78	1.75

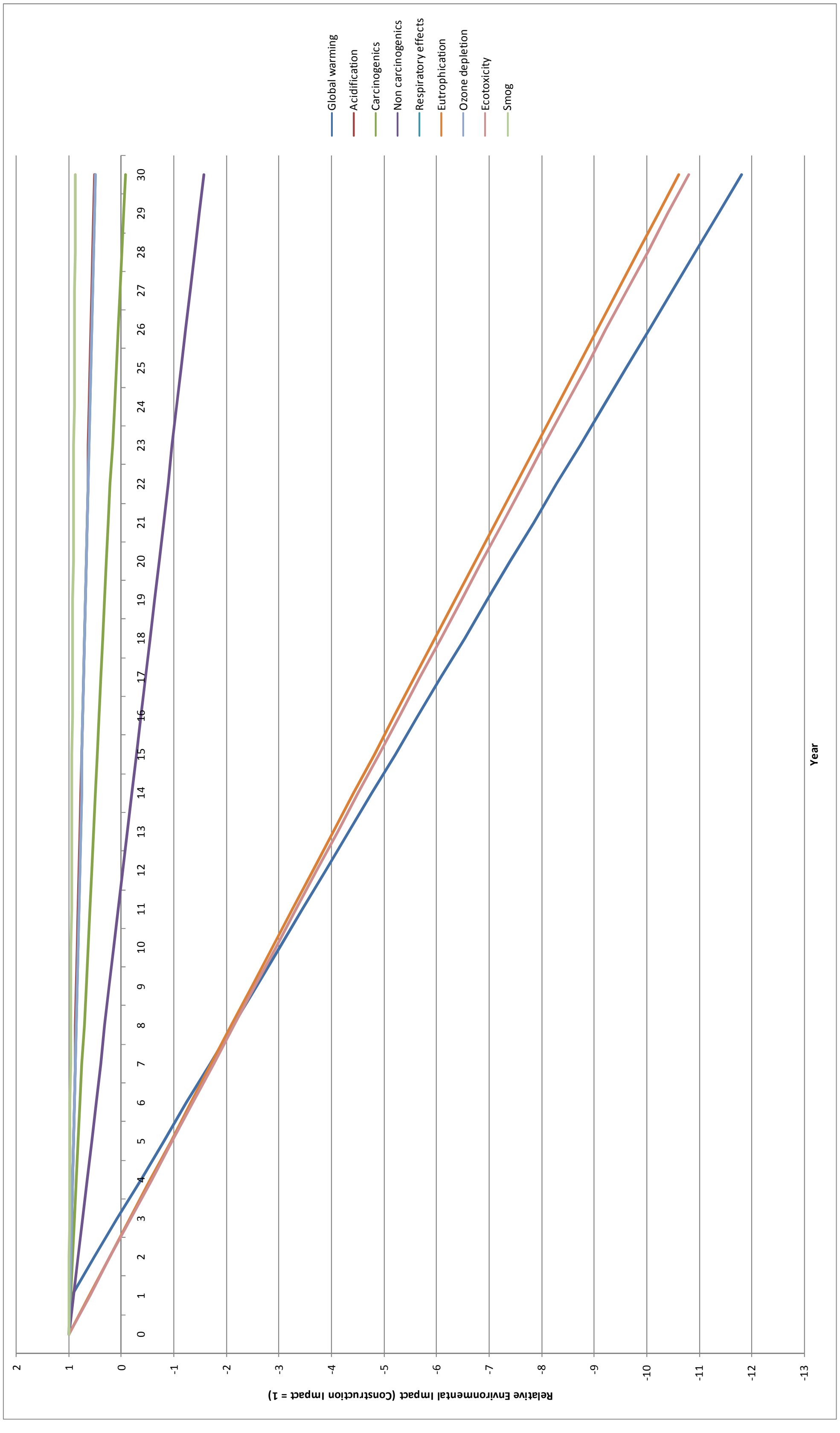
G.4 Total Phosphorous (TP)

Year	Inflow (cf)	Outflow (cf)	Volume Removed (cf)	TPI (mg/L)	TPI (kg)	TPO (mg/L)	TPO (kg)	TP Removed (kg)
2003	67,385	26,933	40,453	0.68	1.29	0.62	0.47	0.82
2004	88,572	52,399	36,173	0.58	1.46	0.97	1.45	0.01
2005	60,610	31,490	29,119	0.74	1.28	0.72	0.64	0.64
2006	90,236	45,194	45,042	0.94	2.39	0.92	1.17	1.22
2007	66,624	31,944	34,680	0.78	1.47	0.64	0.58	0.90
2008	53,022	24,945	28,078	0.85	1.27	0.76	0.54	0.73
2009	87,281	44,783	42,498	1.28	3.16	0.08	0.11	3.05
2010	70,865	52,111	18,754	1.76	3.52	1.24	1.83	1.70
Average			34,350		1.98		0.85	1.13

APPENDIX H: RAIN GARDEN OPERATION PHASE CALCULATIONS

H.1 Operation phase timeline

Total Annual Benefits	2174.90141		82.542105		0.5564524		3759.6665		0.43783563		2.629958008		6.15181E-06		671.79486		0.44761798	
Impact Category	Global warming	Global warming	Acidification	Acidification	Carcinogenics	Carcinogenics	Non carcinogenics	Non carcinogenics	Respiratory effects	Respiratory effects	Eutrophication	Eutrophication	Ozone depletion	Ozone depletion	Ecotoxicity	Ecotoxicity	Smog	Smog
Year	kg CO2 eq	%	H+ moles eq	%	kg benzen eq	%	kg toluen eq	%	kg PM2.5 eq	%	kg N eq	%	kg CFC-11 eq	%	kg 2,4-D eq	%	g NOx eq	%
0	4941.9929	1	5109.4035	1	15.370104	1	43941.291	1	25.681334	1	6.7943771	1	0.000359801	1	1709.3686	1	112.93331	1
1	4710	0.95307561	5027	0.98384506	15	0.963796445	40182	0.91443887	25	0.982951212	4	0.612921395	0.000354	0.98290219	1038	0.606992395	112	0.996036
2	2535	0.512989707	4944	0.967690121	14	0.927592891	36422	0.828877741	25	0.965902423	2	0.225842791	0.000347	0.96580438	366	0.213984789	112	0.992073
3	360	0.072903804	4862	0.951535181	14	0.891389336	32662	0.743316611	24	0.948853635	-1	-0.161235814	0.000341	0.94870657	-306	-0.179022816	112	0.988109
4	-1815	-0.3671821	4779	0.935380242	13	0.855185781	28903	0.657755481	24	0.931804846	-4	-0.548314419	0.000335	0.93160876	-978	-0.572030421	111	0.984146
5	-3990	-0.807268003	4697	0.919225302	13	0.818982227	25143	0.572194351	23	0.914756058	-6	-0.935393023	0.000329	0.914510949	-1650	-0.965038026	111	0.980182
6	-6164	-1.247353907	4614	0.903070362	12	0.782778672	21383	0.486633222	23	0.897707269	-9	-1.322471628	0.000323	0.897413139	-2321	-1.358045632	110	0.976219
7	-8339	-1.68743981	4532	0.886915423	11	0.746575118	17624	0.401072092	23	0.880658481	-12	-1.709550233	0.000317	0.880315329	-2993	-1.751053237	110	0.972255
8	-10514	-2.127525713	4449	0.870760483	11	0.710371563	13864	0.315510962	22	0.863609693	-14	-2.096628838	0.000311	0.863217519	-3665	-2.144060842	109	0.968292
9	-12689	-2.567611617	4367	0.854605543	10	0.674168008	10104	0.229949832	22	0.846560904	-17	-2.483707442	0.000304	0.846119709	-4337	-2.537068447	109	0.964328
10	-14864	-3.00769752	4284	0.838450604	10	0.637964454	6345	0.144388703	21	0.829512116	-20	-2.870786047	0.000298	0.829021899	-5009	-2.930076053	108	0.960364
11	-17039	-3.447783424	4201	0.822295664	9	0.601760899	2585	0.058827573	21	0.812463327	-22	-3.257864652	0.000292	0.811924089	-5680	-3.323083658	108	0.956401
12	-19214	-3.887869327	4119	0.806140725	9	0.565557344	-1175	-0.026733557	20	0.795414539	-25	-3.644943256	0.000286	0.794826279	-6352	-3.716091263	108	0.952437
13	-21389	-4.32795523	4036	0.789985785	8	0.52935379	-4934	-0.112294687	20	0.77836575	-27	-4.032021861	0.000280	0.777728468	-7024	-4.109098868	107	0.948474
14	-23564	-4.768041134	3954	0.773830845	8	0.493150235	-8694	-0.197855816	20	0.761316962	-30	-4.419100466	0.000274	0.760630658	-7696	-4.502106474	107	0.94451
15	-25739	-5.208127037	3871	0.757675906	7	0.45694668	-12454	-0.283416946	19	0.744268174	-33	-4.80617907	0.000268	0.743532848	-8368	-4.895114079	106	0.940547
16	-27913	-5.648212941	3789	0.741520966	6	0.420743126	-16213	-0.368978076	19	0.727219385	-35	-5.193257675	0.000261	0.726435038	-9039	-5.288121684	106	0.936583
17	-30088	-6.088298844	3706	0.725366027	6	0.384539571	-19973	-0.454539206	18	0.710170597	-38	-5.58033628	0.000255	0.709337228	-9711	-5.681129289	105	0.932619
18	-32263	-6.528384747	3624	0.709211087	5	0.348336016	-23733	-0.540100335	18	0.693121808	-41	-5.967414885	0.000249	0.692239418	-10383	-6.074136895	105	0.928656
19	-34438	-6.968470651	3541	0.693056147	5	0.312132462	-27492	-0.625661465	17	0.67607302	-43	-6.354493489	0.000243	0.675141608	-11055	-6.4671445	104	0.924692
20	-36613	-7.408556554	3459	0.676901208	4	0.275928907	-31252	-0.711222595	17	0.659024231	-46	-6.741572094	0.000237	0.658043798	-11727	-6.860152105	104	0.920729
21	-38788	-7.848642458	3376	0.660746268	4	0.239725353	-35012	-0.796783724	16	0.641975443	-48	-7.128650699	0.000231	0.640945987	-12398	-7.253159711	104	0.916765
22	-40963	-8.288728361	3293	0.644591329	3	0.203521798	-38771	-0.882344854	16	0.624926655	-51	-7.515729303	0.000224	0.623848177	-13070	-7.646167316	103	0.912802
23	-43138	-8.728814264	3211	0.628436389	3	0.167318243	-42531	-0.967905984	16	0.607877866	-54	-7.902807908	0.000218	0.606750367	-13742	-8.039174921	103	0.908838
24	-45313	-9.168900168	3128	0.612281449	2	0.131114689	-46291	-1.053467114	15	0.590829078	-56	-8.289886513	0.000212	0.589652557	-14414	-8.432182526	102	0.904875
25	-47488	-9.608986071	3046	0.59612651	1	0.094911134	-50050	-1.139028243	15	0.573780289	-59	-8.676965117	0.000206	0.572554747	-15086	-8.825190132	102	0.900911
26	-49662	-10.04907197	2963	0.57997157	1	0.058707579	-53810	-1.224589373	14	0.556731501	-62	-9.064043722	0.000200	0.555456937	-15757	-9.218197737	101	0.896947
27	-51837	-10.48915788	2881	0.56381663	0	0.022504025	-57570	-1.310150503	14	0.539682712	-64	-9.451122327	0.000194	0.538359127	-16429	-9.611205342	101	0.892984
28	-54012	-10.92924378	2798	0.547661691	0	-0.01369953	-61329	-1.395711633	13	0.522633924	-67	-9.838200931	0.000188	0.521261317	-17101	-10.00421295	100	0.88902
29	-56187	-11.36932968	2716	0.531506751	-1	-0.049903085	-65089	-1.481272762	13	0.505585135	-69	-10.22527954	0.000181	0.504163506	-17773	-10.39722055	100	0.885057
30	-58362	-11.80941559	2633	0.515351812	-1	-0.086106639	-68849	-1.566833892	13	0.488536347	-72	-10.61235814	0.000175	0.487065696	-18444	-10.79022816	100	0.881093


Global warming
Acidification
Carcinogenics
Non carcinogenics
Respiratory effects
Eutrophication
Ozone depletion
Ecotoxicity
Smog
Year
Relative Environmental Impact (Construction Impact = 1)

H.2 Operation phase offset summary

Impact Category	Projected Break-Even Year
Global warming	4
Acidification	62
Carcinogenics	28
Non carcinogenics	12
Respiratory effects	59
Eutrophication	3
Ozone depletion	59
Ecotoxicity	3
Smog	253

APPENDIX I: RAIN GARDEN COMPLETE LCA IMPACT SUMMARY

I.1 Media reuse decommissioning scenario

Impact Category	Unit	Construction Phase	Operation Phase	Decomissioning Phase	Total LCA Impact	Impact per Acre Imp. DA
Global warming	kg CO2 eq	4,942	-63,304	134	-58,228	-116,456
Acidification	H+ moles eq	5,109	-2,476	72	2,705	5,411
Carcinogenics	kg benzen eq	15	-16.69	0.07	-1.26	-2.51
Non carcinogenics	kg toluen eq	43,941	-112,790	552	-68,297	-136,594
Respiratory effects	kg PM2.5 eq	26	-13.14	0.27	12.82	25.64
Eutrophication	kg N eq	7	-78.90	0.18	-71.92	-143.84
Ozone depletion	kg CFC-11 eq	0.0004	-0.000185	0.000016	0.000192	0.000383
Ecotoxicity	kg 2,4-D eq	1,709	-20,154	44	-18,401	-36,801
Smog	g NOx eq	113	-13.43	1.56	101.06	202.12
Onsite labor	hrs	236	60	40	336	672
Cost	2001 USD	31,454	1,260	5,544	38,258	76,516

I.2 Media disposal decommissioning scenario

Impact Category	Unit	Construction Phase	Operation Phase	Decomissioning Phase	Total LCA Impact	Impact per Acre Imp. DA
Global warming	kg CO2 eq	4,942	-63,304	51,291	-7,071	-14,143
Acidification	H+ moles eq	5,109	-2,476	1,340	3,973	7,947
Carcinogenics	kg benzen eq	15	-16.69	17,227	17,226	34,452
Non carcinogenics	kg toluen eq	43,941	-112,790	557,313,182	557,244,333	1,114,488,666
Respiratory effects	kg PM2.5 eq	26	-13.14	4.07	16.62	33.23
Eutrophication	kg N eq	7	-78.90	631.85	559.75	1,119.50
Ozone depletion	kg CFC-11 eq	0.0004	-0.000185	0.000378	0.000553	0.001106
Ecotoxicity	kg 2,4-D eq	1,709	-20,154	4,158,604	4,140,160	8,280,320
Smog	g NOx eq	113	-13.43	28.55	128.05	256.11
Onsite labor	hrs	236	60	40	336	672
Cost	2001 USD	31,454	1,260	5,994	38,708	77,416

APPENDIX J: GREEN ROOF CONSTRUCTION DOCUMENTS

J.1 CEER green roof components and specifications memo

Green Roof Service LLC

Jacob Bulk
CDI, Contractors Diversified, Inc.

30700 Solon Industrial Parkway
Solon, Ohio 44139

June 5th, 2006

By email: jbulk@contractorsdiversified.com 1 pages

Re: Living Roof
Center for Engineering and Research Building (CEER), Villanova University
800 Lancaster Ave. Villanova, PA

Dear Jacob,

We are pleased to provide more detailed information for the living roof.

Components, Specifications:

1. Protection Fabric
   Optigreen Standard Protection Mat, $500g/m^2$
2. Retaining Edge
   Optigreen Retaining Edge, 100mm x 150mm x 2000mm,
   high-strength aluminum alloy, 1,5 mm.
3. Optigreen Drain Plates, 25mm waffled plastic sheet made of recycled PP.
4. Optigreen Separation and Filter Fabric, non-clogging $200g/m^2$, recycled PP geotextile.
5. Rooflite extensive green roof growing media, 4" thick. FLL certified.
6. Gravel, River Rock in between perimeter and retaining edge 1" thick.
7. Plants, minimum 12 different Sedum varieties and 5 different perennials that suit for the proposed system. 3 plugs per square foot.

All components are single sourced and according the FLL guideline. Optigreen is the world leader in the green roof industry and has supplied the components on many millions square feet of green roofs.

GREEN ROOF SERVICE, LLC • 9 Lockhart Circle Suite J • Forest Hill • Maryland • 21050 • USA
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GREEN ROOF SERVICE LLC

The specified system represents a typical, reliable and low maintenance extensive green roof system.

Maximum water retention:

1. Protection fabric: dry 500g/m^2 - saturated 1500 g/m^2
2. Retaining Edge: --------
3. Optigreen Drain Plates: dry 1500 g/m^2 - saturated 6500 g/m^2
4. Optigreen Filter Fabric: dry 200 g/m^2 - saturated 500g/m^2
5. Rooflite extensive* Hydrocks, 4" thick: 75 kg/m^2 - saturated 117 kg/m^2

The system is able to retain (without plants and evaporation) 48.3 ltr/m^2
With plants approximately 50 ltr/m^2 = 4.7 ltr/ft^2 = 1.85 inch rain (w/o evaporation).

Annual water retention according FLL: 60% of annual rainfall.

Sincerely,

Jörg Breuning
Co-Manager

*

- Rooflite extensive with Hydrocks, tested in 2006
- Rooflite extensive with Neosolite, tested in 2005

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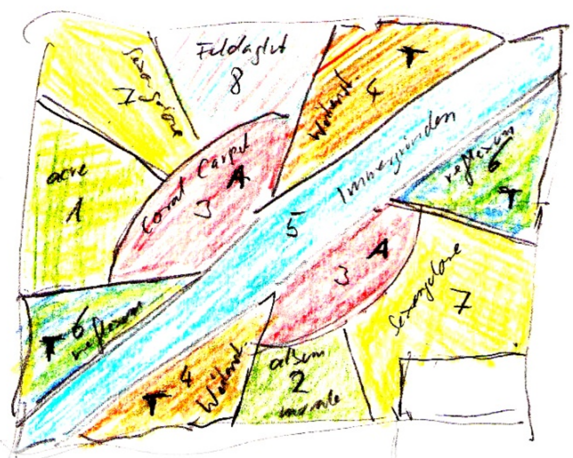
J.2 CEER green roof planting plan

Item	Description	Ordered	Rate	Amount
ALS72	Allium schoenoprasum - Chives, 72 Cell Flat	70	0.61	42.70
SEACA72 1	Sedum acre aureum - Golden Stonecrop, 72 Cell Flat	70	0.61	42.70
SEAM72 2	Sedum album murale, 72 Cell Flat	70	0.61	42.70
SEACC72 3	Sedum album 'Coral Carpet'- Jelly Bean Sedum, 72 Cell Flat	140	0.61	85.40
SEKFWG72 4	Sedum kamtschaticum floriferum 'Weihenstephaner Gold', 72 Cell Flat	140	0.61	85.40
SEHYI72 5	Sedum hybridum 'Immergrünchen' - Little Evergreen, 72 Cell Flat	140	0.61	85.40
SERX72 6	Sedum reflexum 'Blue Spruce' - Jenny Stonecrop, 72 Cell Flat	140	0.61	85.40
SESX72 7	Sedum sexangulare - Six-Sided Sedum, 72 Cell Flat	140	0.61	85.40
SESPF72 8	Sedum spurium fuldaglut - Dragon's Blood Sedum, 72 Cell Flat	70	0.61	42.70
TAC72	Talinum calycinum - Fameflower, 72 Cell Flat	70	0.61	42.70



J.3 CEER green roof project cost summary

Project:	CEER Green Roof 2006					
Project Cost Summary	Budget Breakdown (Uncommitted)			Project Execution Breakdown (Committed)		
Title	Original Budget	Approved Changes or Budget Increases	Updated Budget (w/Scope Changes)	Revised Budget (incl. all Change Orders)	Total Change Orders to Date	Total Paid To Date
Architectural Fees	$ -	$ -	$ -	$ 1,764.00	$ -	$ (1,764.00)
Indirect Cost	$ -	$ -	$ -	$ -	N/A	$ -
Construction	$ -	$ -	$ -	$ 37,403.00	$ -	$ -
Tel/Data(UNIT)	$ -	$ -	$ -	$ -	$ -	$ -
Testing	$ -	$ -	$ -	$ -	$ -	$ -
Moving	$ -	$ -	$ -	$ -	$ -	$ -
Furnishings & Equipment	$ -	$ -	$ -	$ -	$ -	$ -
Landscaping	$ -	$ -	$ -	$ -	$ -	$ -
Misc 1	$ -	$ -	$ -	$ 2,245.23	$ -	$ -
Misc 2	$ -	$ -	$ -	$ 3,184.82	$ -	$ (3,184.82)
Misc 3	$ -	$ -	$ -	$ -	$ -	$ -
Misc 4	$ -	$ -	$ -	$ -	$ -	$ -
Misc 5	$ -	$ -	$ -	$ -	$ -	$ -
Contingency	$ -	$ -	$ -	$ -	N/A	$ -
TOTALS =	$ -		$ -	$ 44,597.05	$ -	$ (4,948.82)

APPENDIX K: GREEN ROOF CONSTRUCTION MATERIAL QUANTITY CALULATIONS

Materials	Quantity	Units	Density	Units	Mass	Units	Notes and Calculation Assumptions	Life Cycle Database Process
Roofing Tar/Sealant	2.71	cf	72	lb/cf	195.12	lbs	Assume 1/16" layer applied over 520 sf	Bitumen adhesive compound, hot, at plant/RER S
Polystyrene Foam Insulation	86.67	cf	2	lb/cf	173.34	lbs	Styrofoam Brand Deckmate Extruded Polystyrene foam insulation (cradle to cradle certified). Thickness = 2". Assume 45% recycled.	Polystyrene foam slab, 45% recycled, at plant/CH S
Building Protection Mat	520	sf	0.1	lb/sf	52	lbs	Optigreen-building protection mat RMS 500 (regenerative synthetic fiber - Polypropylene/Polyester/Acrylic)	Polypropylene fibres (PP), crude oil based, production mix, at plant, PP granulate without additives EU-27 S
Drainage Layer (HDPE)	520	sf	0.3	lb/sf	156	lbs	Optigreen Drain element FKD 25 (recycled HDPE)	HDPE pipes E
Filter Fabric	520	sf	0.02	lb/sf	10.4	lbs	Optigreen filter mat type 105 (polypropylene fibers)	Polypropylene fibres (PP), crude oil based, production mix, at plant, PP granulate without additives EU-27 S
Retaining Edge Drain	93	lf	27.21	lb/lf	2531	lbs	Optigreen retaining edge (high-strength aluminum alloy) - 100mm x 150 mm x 2000 mm	Aluminium alloy, AlMg3, at plant/RER S
Green Roof Media	65	cf	53	lb/cf	3445	lbs	Rooflite Certified Green Roof Media - Extensive MC	_17 Clay and soil from quarry, EU27
Stone	32	cf	100	lb/cf	3200	lbs	Rock for edge drain.	_16 Sand, gravel and stone from quarry, EU27
Green Roof Plants (Sedums)	1560	plugs	-	-	390	pieces	Assume 4 sedum plugs are equivalent to 1 seedling. 1560 total sedum plugs	Seedlings, at greenhouse, US SE/US
Fertilizer	4	lbs	-	-	4	lbs	Optigreen extensive roof fertilizer	Nitrogen fertilizer, production mix, at plant/US

APPENDIX L: GREEN ROOF CONSTRUCTION PHASE MATERIAL AND LABOR TRANSPORTATION CALCULATIONS

Materials	Origin/Destination	Date	Vehicle	Distance (km)	Total Payload (lbs)	Total Payload (kg)	Transportation Units (kgkm)	Life Cycle Database Process	Notes and Calculation Assumptions
Optigreen Green Roof Components	Rotterdam, Netherlands to Baltimore, MD	?	Sea Freight	6612	2753	1249.0	8258388	Transport, ocean freighter, average fuel mix/US	Assumed shipping route
Optigreen Green Roof Components	Krauchenwies, Germany to Rotterdam, Netherlands	?	Truck	720	2753	1249.0	899280	Transport, lorry 16-32t, EURO3/RER S	Assumed shipping route
Optigreen Green Roof Components	Baltimore, MD to Villanova University	7/24/2006	Truck	135	2753	1249.0	168615	Transport, single unit truck, diesel powered/US	From Optigreen US warehouse to green roof site
Green Roof Media	Skyland USA, LLC. 705 Penn Green Road, Avondale, PA 19311	7/31/2006	Truck	50	3445	1562.6	78131	Transport, combination truck, diesel powered/US	-
Stone	Catanach Quarry - 660 Morehall Road, Frazer, PA 19355 - 610-647-4094	7/31/2006	Truck	26	3200	1451.5	37739	Transport, combination truck, diesel powered/US	Assume stone from local quarry
Green Roof Plants (Sedums)	Emory Knoll Farms - 3410 Ady Road, Street, MD 21154	7/31/2006	Truck	95	390	176.9	16806	Transport, combination truck, average fuel mix/US	Assume 0.25 lbs per plug. 1560 plugs total.
Laborers	N. Abbonizio Contractors, Inc. - 1250 Conshohocken Road, Conshohocken, PA 19428 - 610-275-8540	7/24/2006, 7/31/2006	Truck	13.7	1480	671.3	9197	US: Transport, single unit truck, gasoline powered	Assume four laborers weighing 185 lbs each and 2 total trips to the site. Assume same GC as rain garden construction.
Foreman	N. Abbonizio Contractors, Inc. - 1250 Conshohocken Road, Conshohocken, PA 19428 - 610-275-8540	7/24/2006, 7/31/2006	Truck	13.7	370	167.8	2299	US: Transport, single unit truck, gasoline powered	Assume one foreman weighing 185 lbs and 2 total trips to the site. Assume same GC as rain garden construction.

APPENDIX M: GREEN ROOF ENERGY CALCULATOR

M.1 Energy calculator input

Parameter	Value	Units	Notes
State/Province	Pennsylvania	-	-
City	Philadelphia	-	-
Total area of roof	20000	sf	CEER Building footprint measured from aerial imagery
Type of building	New office building	-	-
Growing media depth	4	in	-
Leaf area index	4		Estimated from site inspection
Green roof % of total roof area	3	%	-
Electricity utility rate	0.0787	$ per kWh	UGI Utilities rate as of June 1, 2011
Gas utility rate	0.7359	$ per therm	UGI Utilities rate as of June 1, 2011. Assume 1030 BTU/cf natural gas

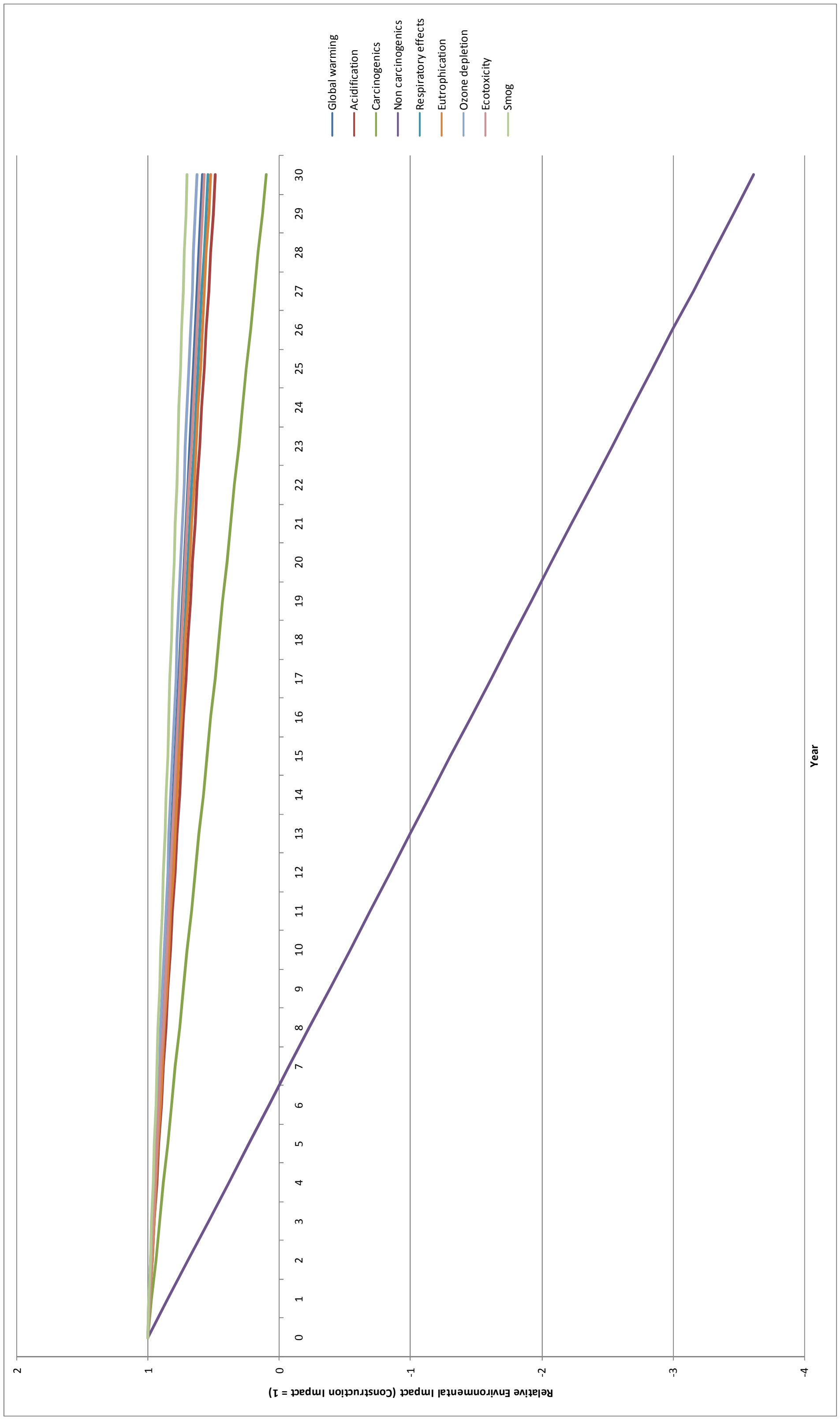
M.2 Energy calculator output

Parameter	Value	Units
Electrical Savings	81.54	kWh
Gas Savings	6.75	Therms
Total Energy Cost Savings	11.52	2011 USD

APPENDIX N: GREEN ROOF OPERATIONAL PHASE CALCULATIONS

N.1 Operation phase timeline

Total Annual Benefits	106.890033		24.3681418		1.099629406		31305.57396		0.128834251		0.317384599		4.77095E-06		422.9641873		0.145387359	
Impact Category	Global warming	Global warming	Acidification	Acidification	Carcinogenics	Carcinogenics	Non carcinogenics	Non carcinogenics	Respiratory effects	Respiratory effects	Eutrophication	Eutrophication	Ozone depletion	Ozone depletion	Ecotoxicity	Ecotoxicity	Smog	Smog
Year	kg CO2 eq	%	H+ moles eq	%	kg benzen eq	%	kg toluen eq	%	kg PM2.5 eq	%	kg N eq	%	kg CFC-11 eq	%	kg 2,4-D eq	%	g NOx eq	%
0	7603.41	1	1434.3642	1	36.624303	1	203781.23	1	8.5153883	1	20.072632	1	0.000380437	1	29521.368	1	14.806905	1
1	7530	0.990308292	1410	0.983011189	36	0.969975418	172476	0.846376558	8	0.98487042	20	0.984188192	0.000376	0.987459301	29098	0.985672609	15	0.990181
2	7423	0.976250121	1386	0.966022379	34	0.939950835	141170	0.692753116	8	0.969740839	19	0.968376384	0.000371	0.974918602	28675	0.971345218	15	0.980362
3	7316	0.962191951	1361	0.949033568	33	0.909926253	109865	0.539129674	8	0.954611259	19	0.952564577	0.000366	0.962377903	28252	0.957017826	14	0.970543
4	7209	0.94813378	1337	0.932044757	32	0.87990167	78559	0.385506232	8	0.939481679	19	0.936752769	0.000361	0.949837205	27830	0.942690435	14	0.960724
5	7102	0.93407561	1313	0.915055947	31	0.849877088	47253	0.23188279	8	0.924352098	18	0.920940961	0.000357	0.937296506	27407	0.928363044	14	0.950906
6	6995	0.92001744	1288	0.898067136	30	0.819852505	15948	0.078259348	8	0.909222518	18	0.905129153	0.000352	0.924755807	26984	0.914035653	14	0.941087
7	6888	0.905959269	1264	0.881078325	29	0.789827923	-15358	-0.075364094	8	0.894092938	18	0.889317345	0.000347	0.912215108	26561	0.899708262	14	0.931268
8	6781	0.891901099	1239	0.864089515	28	0.75980334	-46663	-0.228987536	7	0.878963357	18	0.873505538	0.000342	0.899674409	26138	0.885380871	14	0.921449
9	6675	0.877842929	1215	0.847100704	27	0.729778758	-77969	-0.382610978	7	0.863833777	17	0.85769373	0.000337	0.88713371	25715	0.871053479	13	0.91163
10	6568	0.863784758	1191	0.830111893	26	0.699754175	-109275	-0.536234419	7	0.848704196	17	0.841881922	0.000333	0.874593012	25292	0.856726088	13	0.901811
11	6461	0.849726588	1166	0.813123083	25	0.669729593	-140580	-0.689857861	7	0.833574616	17	0.826070114	0.000328	0.862052313	24869	0.842398697	13	0.891992
12	6354	0.835668418	1142	0.796134272	23	0.63970501	-171886	-0.843481303	7	0.818445036	16	0.810258306	0.000323	0.849511614	24446	0.828071306	13	0.882173
13	6247	0.821610247	1118	0.779145462	22	0.609680428	-203191	-0.997104745	7	0.803315455	16	0.794446499	0.000318	0.836970915	24023	0.813743915	13	0.872354
14	6140	0.807552077	1093	0.762156651	21	0.579655845	-234497	-1.150728187	7	0.788185875	16	0.778634691	0.000314	0.824430216	23600	0.799416524	13	0.862536
15	6033	0.793493907	1069	0.74516784	20	0.549631263	-265802	-1.304351629	7	0.773056295	15	0.762822883	0.000309	0.811889517	23177	0.785089132	13	0.852717
16	5926	0.779435736	1044	0.72817903	19	0.51960668	-297108	-1.457975071	6	0.757926714	15	0.747011075	0.000304	0.799348819	22754	0.770761741	12	0.842898
17	5819	0.765377566	1020	0.711190219	18	0.489582098	-328414	-1.611598513	6	0.742797134	15	0.731199267	0.000299	0.78680812	22331	0.75643435	12	0.833079
18	5713	0.751319396	996	0.694201408	17	0.459557515	-359719	-1.765221955	6	0.727667554	14	0.715387459	0.000295	0.774267421	21908	0.742106959	12	0.82326
19	5606	0.737261225	971	0.677212598	16	0.429532933	-391025	-1.918845397	6	0.712537973	14	0.699575652	0.000290	0.761726722	21485	0.727779568	12	0.813441
20	5499	0.723203055	947	0.660223787	15	0.39950835	-422330	-2.072468839	6	0.697408393	14	0.683763844	0.000285	0.749186023	21062	0.713452177	12	0.803622
21	5392	0.709144885	923	0.643234976	14	0.369483768	-453636	-2.226092281	6	0.682278813	13	0.667952036	0.000280	0.736645324	20639	0.699124785	12	0.793803
22	5285	0.695086714	898	0.626246166	12	0.339459185	-484941	-2.379715723	6	0.667149232	13	0.652140228	0.000275	0.724104626	20216	0.684797394	12	0.783984
23	5178	0.681028544	874	0.609257355	11	0.309434603	-516247	-2.533339165	6	0.652019652	13	0.63632842	0.000271	0.711563927	19793	0.670470003	11	0.774166
24	5071	0.666970373	850	0.592268544	10	0.27941002	-547553	-2.686962607	5	0.636890072	12	0.620516613	0.000266	0.699023228	19370	0.656142612	11	0.764347
25	4964	0.652912203	825	0.575279734	9	0.249385438	-578858	-2.840586049	5	0.621760491	12	0.604704805	0.000261	0.686482529	18947	0.641815221	11	0.754528
26	4857	0.638854033	801	0.558290923	8	0.219360855	-610164	-2.994209491	5	0.606630911	12	0.588892997	0.000256	0.67394183	18524	0.62748783	11	0.744709
27	4751	0.624795862	776	0.541302112	7	0.189336273	-641469	-3.147832933	5	0.591501331	12	0.573081189	0.000252	0.661401131	18101	0.613160438	11	0.73489
28	4644	0.610737692	752	0.524313302	6	0.15931169	-672775	-3.301456375	5	0.57637175	11	0.557269381	0.000247	0.648860432	17678	0.598833047	11	0.725071
29	4537	0.596679522	728	0.507324491	5	0.129287108	-704080	-3.455079817	5	0.56124217	11	0.541457574	0.000242	0.636319734	17255	0.584505656	11	0.715252
30	4430	0.582621351	703	0.49033568	4	0.099262525	-735386	-3.608703258	5	0.546112589	11	0.525645766	0.000237	0.623779035	16832	0.570178265	10	0.705433


Global warming
Acidification
Carcinogenics
Non carcinogenics
Respiratory effects
Eutrophication
Ozone depletion
Ecotoxicity
Smog
Relative Environmental Impact (Construction Impact = 1)
Year
2
1
0
-1
-2
-3
-4
0
1
2
3
4
5
6
7
8
9
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N.2 Operation phase offset summary

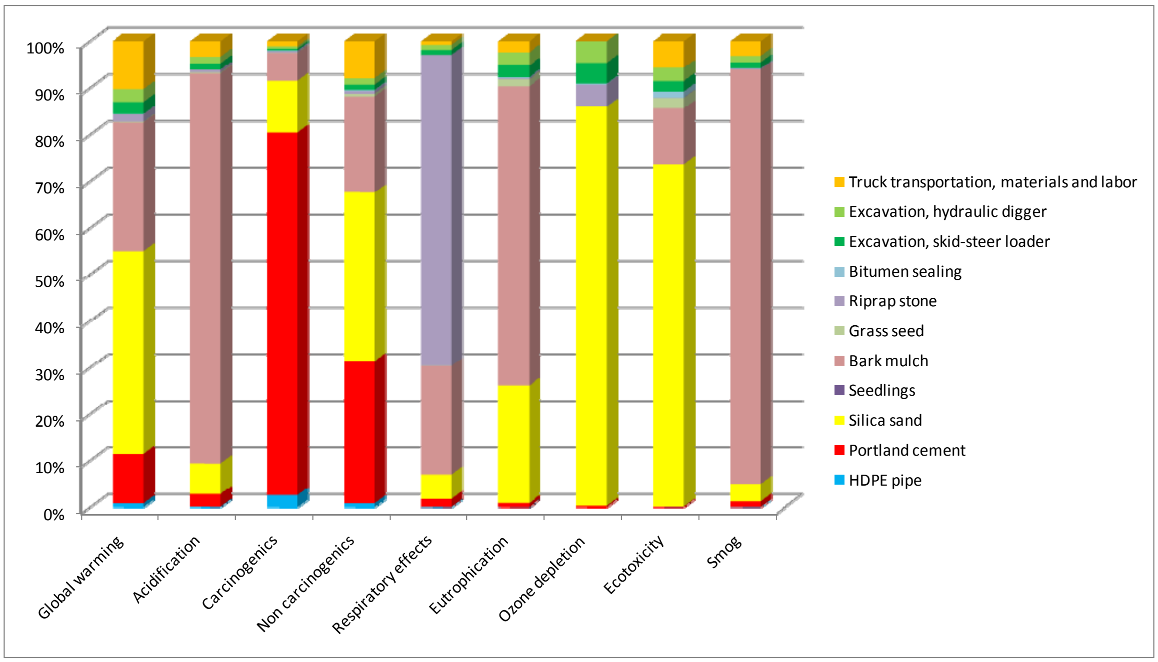
Impact Category	Projected Break-Even Year
Global warming	72
Acidification	59
Carcinogenics	34
Non carcinogenics	7
Respiratory effects	67
Eutrophication	64
Ozone depletion	80
Ecotoxicity	70
Smog	102

APPENDIX O: GREEN ROOF COMPLETE LCA IMPACT SUMMARY

Impact Category	Unit	Construction Phase	Operation Phase	Decomissioning Phase	Total LCA Impact	Impact per Acre Imp. DA
Global warming	kg CO2 eq	7,603	-3,174	1,929	6,359	532,684
Acidification	H+ moles eq	1,434	-731	66	769	64,459
Carcinogenics	kg benzen eq	37	-33	600	603	50,546
Non carcinogenics	kg toluen eq	203,781	-939,167	19,404,515	18,669,129	1,563,898,576
Respiratory effects	kg PM2.5 eq	8.52	-3.87	0.21	4.86	407.45
Eutrophication	kg N eq	20.07	-9.52	23.98	34.53	2,892.81
Ozone depletion	kg CFC-11 eq	0.000380	-0.000143	0.000018	0.000255	0.021366
Ecotoxicity	kg 2,4-D eq	29,521	-12,689	144,853	161,685	13,544,225
Smog	g NOx eq	14.81	-4.36	1.42	11.86	993.70
Onsite labor	hrs	96	42	36	174	14,576
Cost	2006 USD	44,597	3,470	1,780	49,847	4,175,607

APPENDIX P: RAIN GARDEN CONSTRUCTION PHASE IMPACT EXPLORATION

Impact category	Unit	Total	HDPE pipe	Portland cement	Silica sand	Seedlings	Bark mulch	Grass seed	Riprap stone	Bitumen sealing	Excavation, skid-steer loader	Excavation, hydraulic digger	Truck transportation, materials and labor
Global warming	kg CO2 eq	4,941.99	44.44	521.21	2,150.43	0.01	1,366.82	6.56	77.78	2.72	131.18	134.96	505.88
Acidification	H+ moles eq	5,109.404	9.040	139.464	332.167	0.003	4,277.148	10.279	30.529	0.845	71.167	71.875	166.887
Carcinogenics	kg benzen eq	15.37	0.410	11.963	1.698	0.000	0.921	0.014	0.052	0.013	0.059	0.075	0.165
Non carcinogenics	kg toluen eq	43,941.29	392.43	13,414.49	15,898.33	0.03	9,055.86	256.39	257.09	87.24	493.86	600.09	3,485.48
Respiratory effects	kg PM2.5 eq	25.68	0.030437	0.448039	1.344204	0.000006	5.975811	0.005553	17.139603	0.005318	0.266325	0.274703	0.191336
Eutrophication	kg N eq	6.79	0.003865	0.060040	1.715443	0.000004	4.360002	0.104524	0.014289	0.013353	0.173471	0.190110	0.159275
Ozone depletion	kg CFC-11 eq	0.00036	0.00000	0.00000	0.00031	0.00000	0.00000	0.00000	0.00002	0.00000	0.00002	0.00002	0.00000
Ecotoxicity	kg 2,4-D eq	1,709.37	0.064	3.363	1,254.215	0.001	205.653	39.120	1.633	21.543	38.102	48.883	96.793
Smog	g NOx eq	112.93	0.0854	1.4085	4.2682	0.0001	100.2970	0.0278	0.2862	0.0062	1.5390	1.5466	3.4684



APPENDIX Q: GREEN ROOF CONSTRUCTION PHASE IMPACT EXPLORATION

Impact category	Unit	Total	Roofing Tar/Sealant	Polystyrene foam insulation	Polypropylene building protection mat	HDPE underdrain	Polypropylene filter mat	High strength aluminum alloy retaining edge and drain	Certified green roof media	Riprap stone	Sedum plants	Fertilizer	Telescopic boom material handler	Ocean freighter transport, materials	Truck transportation, materials and labor
Global warming	kg CO2 eq	7,603.41	50.13	200.12	54.66	216.42	10.93	6,668.20	20.50	10.79	0.01	3.52	1.42	152.44	214.25
Acidification	H+ moles eq	1,434.364	24.163	28.231	10.846	57.201	2.169	1,053.272	4.937	2.535	0.006	1.849	0.772	175.579	72.801
Carcinogenics	kg benzen eq	36.62	0.092	0.184	0.019	1.600	0.004	34.486	0.000	0.000	0.000	0.001	0.001	0.049	0.189
Non carcinogenics	kg toluen eq	203,781.23	859.05	4,337.80	181.52	1,532.75	36.30	193,888.02	0.00	0.00	0.07	22.48	5.36	1,033.07	1,884.80
Respiratory effects	kg PM2.5 eq	8.52	0.112762	0.115185	0.040736	0.202400	0.008147	7.636007	0.033211	0.016966	0.000013	0.008142	0.002891	0.169030	0.169899
Eutrophication	kg N eq	20.07	0.206714	0.083773	0.005769	0.025925	0.001154	19.360046	0.002899	0.001447	0.000009	0.000302	0.001883	0.167079	0.215634
Ozone depletion	kg CFC-11 eq	0.00038	0.00004	0.00001	0.00000	0.00000	0.00000	0.00030	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00003
Ecotoxicity	kg 2,4-D eq	29,521.37	53.374	101.453	0.798	0.291	0.160	29,219.354	0.000	0.000	0.002	0.339	0.414	28.689	116.495
Smog	g NOx eq	14.81	0.1672	0.4810	0.0938	0.4606	0.0188	8.2172	0.0016	0.0007	0.0001	0.0028	0.0167	3.8025	1.5440