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# Rooftop Gardening in an Urban Setting: Impacts and Implications

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# ROOFTOP GARDENING IN AN URBAN SETTING:
# IMPACTS AND IMPLICATIONS

A Thesis

Submitted to the Bayer School of Natural & Environmental Sciences

Duquesne University

In partial fulfillment of the requirements for

the degree of Master of Science

By

Lisa G. Barreiro

May 2012

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# IMPACTS AND IMPLICATIONS

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Approved March 27, 2012

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# ABSTRACT

## ROOFTOP GARDENING IN AN URBAN SETTING: IMPACTS AND IMPLICATIONS

By

Lisa G. Barreiro

May 2012

Dissertation supervised by John Stolz, Ph.D

Research on green roofs has focused on grasses, sedums, and forbs. The aims of this thesis were to determine the potential of rooftop gardens (RTGs) in an urban setting to reduce local levels of $CO_2$, remediate storm water runoff, and provide boutique vegetables for a restaurant. The garden roof footprint was 238 $ft^2$, with 14% covered by vegetated boxes. The soil mixture used had 96% absorbency with 54.12 gallons of the 55 gallons of precipitation that fell within the rain catcher boxes absorbed. Total biomass production was 37.98 Kg of wet biomass and 5.04 Kg of dry biomass. The amount of $CO_2$ removed equals 0.22 Kg $ft^{-2}$. RTGs have a limited capacity to help sequester $CO_2$, but retain precipitation in amounts similar to green roofs. The restaurant was provided with 4.7 Kg (wet weight) of produce (several varieties of tomatoes, peppers, and eggplant). These results support the utility of RTGs.

# ACKNOWLEDGEMENT

I would like to thank the following people who have helped to make this project possible.

First and foremost, I would like to thank my committee for taking the time to listen and guide me along the way. I would like to thank Dr. Stolz for the loan of essential lab equipment and for providing procedural advice. Your guidance was invaluable to the success of this project. I would like to thank Dr. Tobin for listening to my endless whining over the math and for helping me to understand numeracy. Your calm and patience were invaluable in helping me to be mindful of the knowledge behind the numbers. I would also like to thank Dr. Kabala for allowing me to pop into your office any time I needed to talk and for always having suggestions. You always gave me something new to think about while providing direction on how to get to where I wanted to be. I must especially thank Dr. John Kern of the Mathematics department for the long hours he spent helping me to discover the correct equation. Dr. Kern, without your exceptional teaching ability, I would not have been able to "run the numbers". You gave me methods to use to identify which equations were appropriate to what data set and more importantly, shored up my self-confidence over my numerical results. Thank you all so much for all of the time you spent listening and helping me figure things out.

I must, of course, thank the owner of The BrikRoom in South Side, Pittsburgh for the use of his roof. Greg Coyle generously allowed the building of the structure and maintenance of the garden throughout the growing season, within the parameters of his business hours. Without his roof, this research could not have been conducted. I would also like to acknowledge the help I received with the manual labor. Michael Barreiro,

David Baker and Justin Bumblis all helped to haul water, peat moss cubes and cow manure through the door, up the stairs, through another door, through the office and conference room, out a window, up the ladder, across the control roof, over the peaked roof and onto the RTG, a truly Sisyphean task. Likewise, special thanks must go to the chef of The BrikRoom, Steve Lanzilotta, without whom the garden would have died during my absences. Steve, thanks for "making it rain" as often as you did and for tracking and weighing the produce you harvested.

I would also like to thank Dr. Mary Alleman for providing a food-safe lab space and allowing me full access throughout the summer. Dr. Gerra Bosco, for so much. Thanks for getting the hose for the RTG and bringing it down, thanks for listening to me chatter about my project all those times and thank you so much for the opportunity to work by your side and learn from you. You are an amazing teacher and you truly do "teach like your hair is on fire" every single day.

Finally, I must thank, above all, Michael Barreiro for his constant support throughout this project. Mikey, thanks for listening to me, supporting me, helping me carry and tote, and driving me hither and yon.

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# Chapter 1 Introduction

Green roofs have been studied quite extensively over the past few decades, in part due to the success of Germany's incentive programs in the 20th century (Kohler 2008). However, the majority of green roofs studied have included only grasses, sedums, forbs and the like as research demonstrated that only certain plants can survive the extreme conditions of rooftops (Dunnett, et al. 2008). In the past decade, members of the public have begun to produce food crops, known as urban farming, on private rooftops for personal or community use (Germain, et al. 2008; Woessner 2011; Urban Agriculture Notes 2003). Research is very limited into this type of rooftop and it is not known whether rooftop gardens (RTGs) can provide similar benefits as seen with extensive roofs, in addition to providing other benefits not found in extensive, monoculture roofing systems.

# Chapter 2 Background

Ecoroofs date back centuries but the environmental benefits have only recently been considered. Early green roofs were used simply because the materials – readily available and cheap – provided an effective covering for the dwelling (Getter and Rowe 2006). Modern iterations of green roofs emerged in the late 1970s, when Germany began to encourage new construction to include plantings as part of the building structure. The German government was so convinced of the benefits of green roofs that it implemented an incentive program in the early 1980s that lasted almost twenty years (Kohler 2008). The environmental benefits observed include storm-water runoff management, energy conservation through temperature stabilization, and urban habitat preservation, although other benefits such as aesthetic value and biodiversity, have also been noted.

There are many descriptors for ecoroofs, including intensive/extensive, living roofs, garden roofs, and high-maintenance/low-maintenance roofs. While different types of ecoroofs differ in use and design, they can be separated into two basic categories – those that require maintenance and those that don't. For the purposes of this paper, the following definitions will apply: **Extensive** roofs are those that require little maintenance, are established over the majority of the roof area and generally contain low-growing, drought- and extreme weather-tolerant plants; **Intensive** roofs require high maintenance, may or may not cover the majority of the roof and usually contain a variety of plants, such as small trees or shrubs. The term **rooftop gardens** (**RTGs**) will be used for gardens built on a roof that has the same material constituents as a backyard garden planted with small-scale crops.

Traditionally, extensive roofs use a variety of sedum, which is a low-growing, low-maintenance, drought-tolerant ground cover seen in many landscapes and rock gardens. These plants are easy to grow, spread quickly and generally tend to crowd out other less-desirable plants. Most research that has been done on different types of vegetation has only looked at grasses, forbs, and sedges to determine what effect they have on water retention and this research concluded that broader-leaved plants with deeper root systems than sedums appear to retain more runoff. However, it was unclear whether this was due to the leaf structure or the depth of the substrate (Dunnett, et al. 2008).

Intensive roofs have rarely been used in urban environments as they require frequent access to the rooftop and extensive maintenance. Therefore, little research has been done on the benefits of these types of roofs. Intensive roofs typically contain larger plants placed over a smaller total area with a higher diversity of plants (Oberndorfer, et al. 2007).

For both intensive and extensive roofs, there are four basic benefits to vegetating a roof as opposed to leaving it bare. Those basic benefits are aesthetic value, environmental impact, storm water management, and building energy reduction (Spolek 2008). Only recently have green roofs been looked at as a way to assist in the reduction of greenhouse gases, such as $CO_2$, and it is this, along with storm water runoff management, that was the focus of this thesis research.

### 2.1.1. Storm water runoff

One of the biggest benefits to the environment is noticed in the area of storm water runoff. According to the US Census Bureau, the world's population will continue to increase to 9 billion by the year 2050, with much of this population moving into urban centers (U.S. Census Bureau 2011). In 1950 when the world population was approximately 2.5 billion people, only 30% of people lived in urban centers. By 2008, the number of people living in urban centers ranged from 44% for less developed countries to as high as 74% in very developed countries, with a projected increase of 70% of the world's population living in an urban center by 2050 (Human Population: Urbanization 2012). As the movement of people from rural to urban settings increases, so do urban problems in terms of food production and pollution management. Additionally, many surfaces that are currently covered with vegetation will be converted to impervious surfaces, thereby increasing the need for storm water management.

In an episode of the television series *Frontline* titled "Poisoned Waters", storm water runoff is shown to be one of the leading causes of water pollution in urban centers

("Poisoned Water" 2009). This pollution consists of silt, dissolved particulates, oil and gasoline from vehicles, and fertilizers. Jay Manning, Director of the State of Washington Department of Ecology, states in "Poisoned Waters," that "…the amount of oil carried into Puget Sound from storm water runoff in a two-year period is equal to the amount of oil spilled from the Exxon Valdez in 1989" ("Poisoned Water" 2009). Without a vegetated roof, rain simply runs off the roof surface, into gutters and into the sewer system. This seriously impacts the quality of water entering groundwater or municipal treatment systems as the runoff collects pollutants and transports it to receiving systems (Getter and Rowe 2006). Ecoroofs can reduce runoff by varying amounts, with some studies showing 100% reduction, indicating that all the water was used by the plants in the ecoroof (Spolek 2008). While recorded retention rates were highly variable due to difficulties with flow meters and associated software, the peak retention was 87% in these studies (Spolek 2008). By reducing the volume of the runoff, a reduction in the pollutants in the waterways is seen, providing a positive impact on municipal water treatment plants. Having a green roof also provides a partial filter in that the rainwater flows through the substrate before reaching the drainage system, providing an opportunity for pollutants to adsorb onto substrate particles. Further opportunities for filtering can be made at the drainage outflow before the water reaches the municipal system, potentially reducing the pollutant load and providing additional reduction in the cost of municipal services as les water must now be treated.

Green roofs can also delay the runoff from entering the sewer systems, reducing the immediate impact on water treatment plants. Two studies showed that runoff from green roofs was delayed by between 10 minutes and one hour on average, as opposed to the immediate runoff from unplanted roofs, with the amount of retention varying based on the amount of precipitation that fell (Spolek 2008), (Simmons, et al. 2008). Simmons et al. saw the 10 minute delay during large rain events (defined as >10 mm) with a complete retention in smaller rain events (defined as <10 mm) (Simmons, et al. 2008). This has important applications for municipalities because it reduces the load on municipal systems during rain events, thereby reducing the possibility of urban flooding during heavy rainfall events (Getter and Rowe 2006). Storm water runoff was a factor in a flooding event in Pittsburgh, PA in July, 2011 that killed four people, due to the inability of the Wastewater Treatment Plant (WWTP) to handle the volume. (Riely 2011)

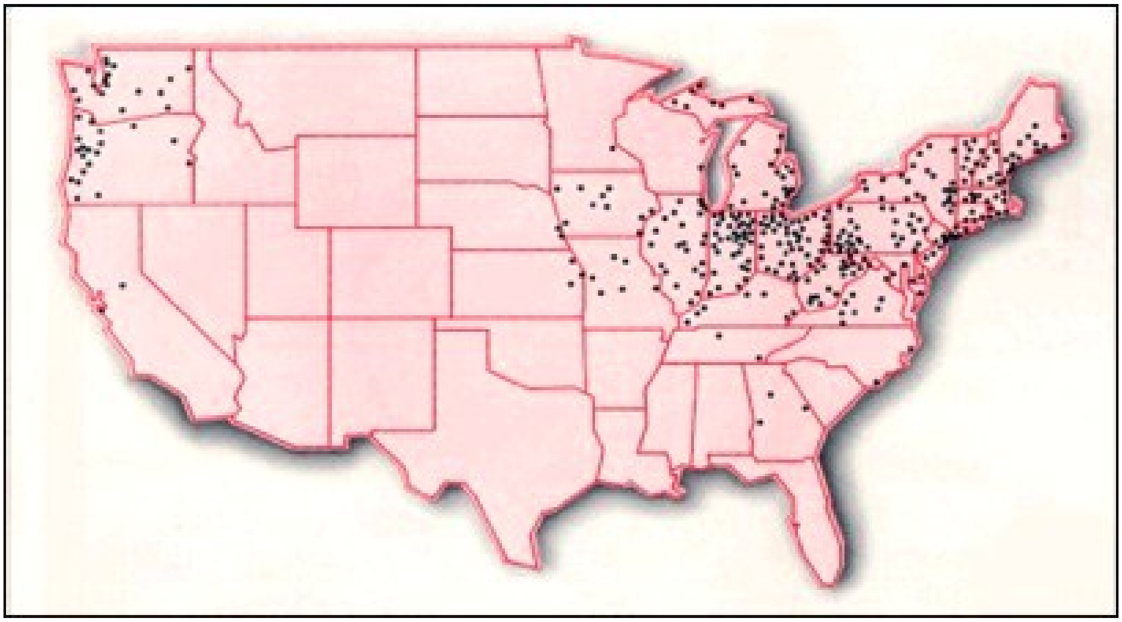


**Figure 1: Map of the 772 cities in United States that have Combined Sewer Systems (CSS). http://cfpub.epa.gov/npdes/cso/demo.cfm?program_id=5, accessed November 14, 2011**

Why runoff delay is important can be seen in cities with Combined Sewer Systems (CSS), which number 772 in the US and are also seen in older cities around the world ("Combined Sewer Overflows" 2011). (Fig. 1) These systems collect residential, commercial and industrial wastewater, along with storm water runoff, in a single conveyance. Ideally, the wastewater is then carried into publically owned treatment works (POTWs) for treatment to remove harmful substances before being discharged into receiving waters. However, during large rain or snowmelt events, the runoff water component is too large for the water treatment system to handle, causing an overflow directly into nearby streams or other water bodies, known as a Combined Sewer Overflow (CSO) event (“Combined Sewer Overflows” 2011). Since the overflow contains untreated sewage, in addition to toxic material and industrial chemicals, the potential for harm to humans and the environment can be substantial. The untreated sewage carries microbial pathogens in the form of bacteria, viruses and parasites, that are responsible for many diseases (“Implementation and Enforcement of the CSO Control Policy”, Ch. 6. 2004). Many of these pathogens are not only present in human excrement, but also in pet waste that, if not removed by the owners, enters the runoff via the sidewalks. Bacteria and viruses exist in sewage in amounts ranging from 0.1 pathogens to as high as $10^7$/100 mL, levels high enough to cause illness. After a CSO event, bacteria (measured by total fecal coliforms) are present in levels ranging from $10^5$ to $10^7$ cts/100 mL with infective doses in some cases within that range. For example, between 30,000 and $10^7$ *E. coli* bacteria are found per 100 mL of untreated sewage with an infective dose between $10^5$ and $10^7$ bacteria (“Implementation and Enforcement of the CSO Control Policy”, Ch. 6 2004). A person’s feces contains approximately $10^8$ *E. coli* bacteria, more than enough to cause illness in another person. Viruses are more problematic as their infective dose is far less. An example can be found in enteroviruses, of which as much as 100,000 pathogens/100 mL are found in sewage and which carries an infective dose of between 1-10 virus particles ("Implementation and Enforcement of the CSO Control Policy", Ch. 6 2004).

Other pathogens that can cause human illness can be found in pet excrement. Pet excrement enters receiving waters during a CSO due to irresponsible pet ownership. An example of an animal-related pathogen is *Leptospira interrogans,* a gram negative spirochete bacteria that is usually found in both domestic and wild animals, such as rats, dogs or cows (NCBI Bookshelf). The bacteria are transmitted via infected urine where humans can contract it through contact with water contaminated by the bacteria. This bacteria can cause liver or kidney failure as they are not removed from the organs during the immune response. Cases have been reported in slums in El Salvador, for example, of open sewers flooding during rain events, introducing the bacteria into drinking water supplies and resulting in increased outbreaks of leptospirosis (Alirol, et al. 2011). However, leptospirosis can occur in any country due to imports of exotic animals. For example, an increase in the canine form of this disease has been present in California since 2000 due to the import of pets (Medscape Reference). Parasites, such as protozoa and helminths (parasitic worms) can also exist in raw sewage. The most common parasitic protozoa are *Giardia lamblia, Cryptosporidium parvum* and *Entamoeba histolytica* ("Implementation and Enforcement of the CSO Control Policy", Ch. 6 2004). It does not require a large amount of these protozoa to cause an infection. In the case of *Cryptosporidium* for example, it only takes one oocyst.

In addition to pathogenic organisms, many organic chemicals and inorganic synthetics can be found in CSOs. These include biologically active chemicals, such as antibiotics, hormones, and pharmaceuticals, which are excreted in metabolite form in urine and feces. While the risk from biologically active chemicals remains unclear in many respects, recently a bill was introduced into Congress to reduce human exposure to these chemicals (Kerry and Moran 2011). The Endocrine Disrupting Chemical Elimination Act of 2011 conceded that enough evidence exists to support the hypothesis that the human endocrine system is adversely affected by particular chemicals and calls for further research into the effects. One example of a chemical that is considered to be an endocrine disrupter is ethinyl estradiol, a synthetic form of estrogen. This chemical can be removed up to 90% from the effluent in a WWTP, but in a CSO that bypasses the WWTP, it is directly discharged to surface waters. Ethinyl estradiol can have a negative developmental effect on aquatic organisms even at low concentrations and with a short exposure (Weyrauch, et al. 2010). If the organism is one that humans consume, like a fish, it can be passed on through bioaccumulation as it is a lipophilic chemical.

In addition, metals and synthetic organic chemicals, such as carbamazepine, sulfamethoxazole and diclofenac, can remain in the environment for decades and are also found in CSOs (“Implementation and Enforcement of the CSO Control Policy”, Ch. 6 2004; Weyrauch, et al. 2010). For instance, Weyrauch et al. determined that pollutants such as industrial compounds ( e.g. polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs)) can easily find their way into treatment systems through industrial discharge pathways and while many of them can be treated in WWTPs, in a storm event they are transported directly into surface waters (Weyrauch, et al. 2010). Soluble metals may precipitate and remain within a sewer system’s sediments during dry weather, and then be released during a rain event (Houhou, et al. 2009). Dissolved metals that can be found in domestic sewage include nickel (Ni), copper (Cu), aluminum (Al), zinc (Zn), lead (Pb), and cadmium (Cd). Metals such as Cd, arsenic (As), and mercury (Hg) are lipophilic and bioaccumulate in fatty organs like the brain, kidneys and liver. These metals cause illnesses such as developmental delays or abnormalities, hair loss and bone disease in humans (“Implementation and Enforcement of the CSO Control Policy”, Ch. 6 2004; Schettler, et al. 2000).

Dissolved Zn, often found in paints, wood preservatives and rust prevention coatings can also be detected in storm water. While zinc is an essential mineral, excessive amounts can cause toxicity, with symptoms ranging from a cough to convulsions and shock (National Institute of Health). Houhou et al. also found a wide range of heavy metal species within the sewer sediments, with the majority of the species found as sulfide minerals. Metal oxides were found, such as zinc dioxide, lead dioxide, titanium oxide, di- and trioxides, along with silicates and stainless steel fragments (Houhou, et al. 2009). All of these chemicals and metals have a high degree of removal at WWTPs, but zero removal when discharged directly into receiving waters, as is seen in CSOs.

While many of the impacts seen for human health are also impacts on the environment as many of the pathogens and chemicals affect aquatic life, there are additional impacts unique to the environment. According to the EPA, the three main sources of pollutants in a CSO event are increased nutrients, increased siltation of streams, and increased pathogens (“Implementation and Enforcement of the CSO Control Policy”, Ch. 5 2002). Each of these pollutants causes a variety of effects, with the biggest impact being seen in water quality and a water body’s ability to sustain aquatic life.

Human and/or animal excrement contain large amounts of organic material that is consumed by bacteria. This consumption results in a high biochemical oxygen demand

(BOD), depleting the level of oxygen in the water body (Cushing and Allen 2001). One example is found in the Indianapolis, IN, water quality assessment of 2001. The report found that CSO discharges were responsible for most of the dissolved oxygen (DO) violations seen in receiving waters, caused by high levels of raw sewage ("Implementation and Enforcement of the CSO Control Policy", Ch. 5 2002). Low levels of DO affect fish life since many species, such as trout, are very sensitive to levels of DO (Carline, et al. 1992). The organic material often contains high levels of nutrients, leading to increased eutrophication, a situation where algae overpopulate an area in response to an increase in available nitrogen. This algal bloom reduces the available oxygen in the water body, causing DO levels to decrease rapidly and resulting in fish kills.

Increased siltation can occur during a CSO as sediments that exist within the combined wastewater/storm water pipeline are mobilized and discharged directly into receiving waters (Houhou, et al. 2009). Heavily silted waters are poor habitats for both invertebrates and fish, as the silt will suffocate any bottom-feeding larvae, in addition to reducing circulation of both water and oxygen (Cushing and Allen 2001). Increased siltation reduces biodiversity as some aquatic organisms, including fish, are highly specific in their choice of habitat. For instance, sculpins lay their eggs on the undersides of large, flat rocks (Cushing and Allen 2001). If the rocks are buried in silt, resulting in loss of breeding ground, sculpins will cease to exist within that habitat, either through extirpation or local extinction. Additionally, increased turbidity caused by siltation inhibits photosynthesis by algae, affecting their ability to reproduce. In streams with low flow, these effects can last several days, during which time algae may die off, affecting the entire food web (Weyrauch, et al. 2010; Cushing 2002).

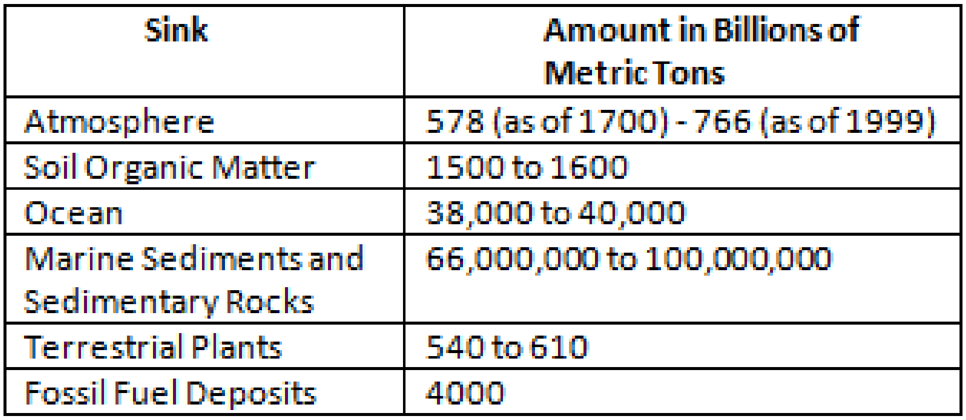
Recreational uses of water bodies are also affected by the three main types of pollutants, and while that does not necessarily constitute a detrimental environmental impact, it is a human impact. One of the biggest challenges associated with recreational impacts is identifying the source of the contamination that is responsible for closings of beaches or other recreational waterways. However, of the events that were able to be identified, 1% of all reported closings in the US were due to a CSO event with the majority due to elevated bacteria levels ("Implementation and Enforcement of the CSO Control Policy", Ch. 5 2002). Another issue deals with floatables, which are visible solids floating in the water, such as sewage-related items, street litter and medical items ("Implementation and Enforcement of the CSO Control Policy", Ch. 5 2002). This type of material is typically removed in the pre-treatment screening process of WWTPs and therefore can be directly traced back to a CSO event. To put this in perspective, during the 2003 Ocean Conservancy International Coastal Cleanup event, more than 7500 condoms and 10,000 tampons and applicators were found over approximately 9,200 miles of US shoreline ("Implementation and Enforcement of the CSO Control Policy", Ch. 5 2002).

### 2.1.2. Pollution abatement from green roofs

Storm water management is not the only benefit that a green roof may provide. Poor air quality has been shown to have a direct negative impact on human health (Mayer 1999; Yang, et al. 2008). Recent news articles in Pittsburgh attributed increased mortality rates for certain diseases (such as heart and respiratory disease and cancer) to the large number of coal-fired power plants prevalent in the region (Hopey and Templeton 2010). These power plants emit particulates, $CO_2$, $NO_x$, and $SO_x$ even with air control technology. RTGs can help to minimize these air pollutants through several ways, two of which are dry deposition and microclimate effects (Yang, et al. 2008). Plants provide a surface for air pollutants to adhere to, effectively turning leaf surfaces into natural sinks. Since plants also provide shade and evapotranspirate, they reduce air temperatures, potentially reducing temperatures enough to inhibit photochemical reactions that contribute to tropospheric ozone. A secondary benefit may be realized through the reduction in energy use for heating and cooling, thereby reducing emissions from power plants (Yang, et al. 2008). Additionally, since plants use photosynthesis to build cellular material and photosynthesis requires $CO_{2,}$ RTGs offer another weapon in the arsenal to help reduce $CO_2$ levels.

Prior to the Industrial Revolution, when primarily natural processes released $CO_2$ into the atmosphere, $CO_2$ uptake by plants kept the earth in a steady state of $CO_2$. $CO_2$ is naturally produced through processes such as respiration and decay of organic matter. Processes that remove $CO_2$ from the atmosphere, such as photosynthesis and diffusion into a water body, work efficiently when no human activity is taken into account. Natural sinks, tie up carbon in various forms so that it can't be released. The major sinks are located in the ocean, plant biomass, fossil fuels and terrestrial and oceanic rock, with the latter being the largest store (Pidwirny and Gulledge 2010) (Table 1). Annually, these sinks store huge amounts of carbon.

**Table 1: Estimated major stores of carbon on the Earth. (Pidwirny and Gulledge 2010)**



| Sink | Amount in Billions of Metric Tons |
|---|---|
| Atmosphere | 578 (as of 1700) - 766 (as of 1999) |
| Soil Organic Matter | 1500 to 1600 |
| Ocean | 38,000 to 40,000 |
| Marine Sediments and Sedimentary Rocks | 66,000,000 to 100,000,000 |
| Terrestrial Plants | 540 to 610 |
| Fossil Fuel Deposits | 4000 |

In 2000, approximately 6.5 Pg of $CO_2$ went back into the atmosphere from fossil fuel burning alone (Pidwirny and Gulledge 2010). With the exponential rise in population, an increase in fossil fuel combustion for energy and vehicle use is also seen, leading to a similar rise in $CO_2$ production. There is little question left in the scientific community that $CO_2$ emissions are increasing at a rapid rate and have been doing so for the last 4 decades. One need only look at the Mauna Loa Observatory data to notice the exponential rise in global rates since 1958. This increase is attributed to human activities, such as the combustion of fossil fuels or land-use practices (U.S. Department of Commerce 2011; Carbon Dioxide) . The Fifth U.S. Climate Action Report states that greenhouse gas (GHG) emissions have increased by more than 17% globally from 1990-2007, with $CO_2$ emissions increasing by 21.8% over the same time period ("Fifth U.S. Climate Action Report" 2010). In 2005 alone, global concentrations of $CO_2$ were 35% higher than before the 1700s (Carbon Dioxide 2011). This trend is expected to continue as demand for energy increases worldwide. Natural processes are no longer sufficient to handle this increase and thus, atmospheric $CO_2$ is on the rise, raising global concern. This has led to regulations throughout Europe, with the US currently considering them.

Most scientists agree that atmospheric $CO_2$ must be reduced in order to alleviate or remove the threat of global climate change (Upadhyay, et al. 2005; Shi, et al. 2009; Farage, et al. 2007). We are left with only two options: reduce $CO_2$ emissions or find additional ways to remove and sequester it.

There are two main methods currently under study for $CO_2$ sequestration. These are injection into geological formations, which not only sequesters but can also chemically change $CO_2$ into other minerals (such as $CaCO_3$), and direct injection into deep-sea sediments, which allows $CO_2$to disassociate in water to form $HCO_3^-$ in addition to sequestration. But for each of these methods, the gas must be first captured and then compressed for transport. Therefore, these methods are only applicable for industries where the $CO_2$ can be captured, such as power plants and other industrial point sources, but none will work with non-point emission sources (Lackner 2003). Each method poses risks to humans, wildlife, and the environment. For instance, two recent earthquakes in Ohio have been attributed to deep well injection of fracking wastewater (Fischetti 2012). Deep well injection is currently being used to sequester $CO_2$ and while there is no indication that this process can cause the same type of earthquake as the fracking water injection, it remains a potential risk. Deep well injection is attractive because it is one of the easiest methods available (Lackner 2003).

### 2.1.3. Deep well injection

Deep well injection is the process of injecting compressed $CO_2$ captured from industrial sources into porous rock formations deep underground. The captured $CO_2$ is then transported through a series of pipelines to deep well injection sites ("Carbon Storage and Sequestration"). The most suitable geological formations for deep well injection include depleted oil and gas fields, unminable coal seams, and saline aquifers (House, et al. 2006).The geological formation that can successfully sequester $CO_2$ has specific requirements, such as having a porous rock with an impermeable top layer (called a caprock), which is a key component for ensuring that the gas does not migrate to the surface. Porous rock has void spaces between the rock particles in which the $CO_2$ becomes trapped. Additionally, the pore spaces of the rock must be connected so that the gas can permeate throughout. Most deep well injection sites are approximately 3000 m below the surface of the earth and at this depth, the $CO_2$ becomes a supercritical fluid. (House, et al. 2006) Once sequestered, the supercritical liquid may react with other fluids naturally occurring within the pore spaces and may form other minerals, effectively ensuring complete sequestration (MRCSP). However, the problems associated with this method are maintenance and upkeep, and disposition of the deep well injection sites once the site reaches capacity. Additional concerns include the possible migration of $CO_2$ to the surface due to the buoyant nature of the gas, and the risk associated with the pipelines used for transport.

The oil and gas industry have successfully used deep-well $CO_2$ injection as a way to stimulate additional oil production in a process known as Enhanced Oil Recovery (EOR) and approximately 30% of what was injected remains safely underground ("Carbon Storage and Sequestration"). Considering that in Texas alone, EOR uses approximately 20 million tons/year of $CO_2$, even 30% of that equates to 6 million tons of $CO_2$ permanently captured underground. However, one major concern with this process is the possibility of migration, which can occur for two reasons, one of which is the density gradient and the other is because of the very porosity that sequestration demands.

The density gradient is formed due to the difference in temperature and pressure. The storage wells are located approximately 1 km deep underground, and at this point, the temperature in the storage wells is much higher than the temperature of supercritical $CO_2$, causing it to be much more buoyant than any fluid that is currently in the pores of the rock and allowing it to easily migrate through any fracture or fissure within the rock formation (House, et al. 2006). One of the best sites for injection are natural gas reservoirs as these are geologically stable and demonstrated to be areas that can lock in gas. However, over the last several decades, these sites have been drilled with a method known as hydraulic fracturing, which fractures the rock in order to allow gas to flow. This fracturing process creates fissures in the impermeable layers, making the potentiality of $CO_2$ migration, should it be injected into these wells, a real concern (House, et al. 2006). Additionally, while the formations chosen to sequester $CO_2$ are able to capture large amounts, they will become full at some point. Once the site becomes full, it must be closed down, capped and maintained indefinitely (Gerard and Wilson 2009). This raises more than a few concerns and identifies several problems which need to be addressed before deep well injection can be considered a globally viable solution. According to Gerard and Wilson, the IPCC report states that "99% of injected $CO_2$ is very likely … to remain in …reservoirs for over 100 years" and this raises questions such as who will pay for continued maintenance in the future, who will pay for any liability should the $CO_2$ seep to the surface and who may pay to clean up any future problems, as is the case with Superfund (Gerard and Wilson 2009). Since rising $CO_2$ levels are a global concern, it must be considered whether regulation should fall to the country in which the sequestration site is located or whether regulation should fall under the auspices of a worldwide regulatory body. The potential for a social and/or economic divide also exist if a country has no suitable geological formation in which to sequester the $CO_2$, as it then must be piped to another country at, it can be assumed, considerable cost. If a country can't afford to have their $CO_2$ taken by another country, then it is likely that it will simply continue to be released into the atmosphere, bypassing the sequestration entirely and effectively negating any benefit that may be seen from other sequestration efforts. Clearly, deep-well injection may not be the best option in all circumstances and therefore does not fully provide an answer to global $CO_2$ sequestration needs.

### 2.1.4. Deep sea injection

There are two ways that $CO_2$ can be injected into the ocean, either into the water or into the ocean floor. Concerns have been raised about the viability of injection directly into the ocean, namely in the form of its effect on marine organisms due to acidification, and also about injection into the ocean floor. Ocean floor injection may result in increased hydrate formation, which could lead to explosions due to obstruction of the pipe.

If $CO_2$ is injected directly into the ocean as a gas, much of it will dissolve as bicarbonate as per the bicarbonate equation. This equation shows that injection of $CO_2$ will result in an increase in hydrogen atoms, which lowers pH, and it is this change that may cause the most concern. Shallow water organisms are able to adjust their metabolisms and internal processes to adapt to changes in acidification, but even in shallow water systems, a change in pH can result in loss of specific species of fish (Carline, et al. 1992). In the deep ocean, since the bottom water can be stable for thousands of years, deep-sea organisms lack the capacity to adapt quickly to changes in pH and any disturbance to the pH level will likely lead to stress resulting in death of the organism should the stress be long-term. This in turn could lead to a decrease in oceanic biodiversity (Seibel and Walsh 2003). For instance, if the partial pressure of $CO_2$ is doubled in a shallow water system, there is only a small (0.02) pH change in the intracellular space of *Stenoteuthis oualaniensis*, a shallow-water squid, but the same doubling in the deep-sea affects *Japetella heathi*, a pelagic octopod, by an order of magnitude (0.2) pH change (Seibel and Walsh 2003). This is due, in part, to the differences of buffering ability between the two organisms but shows that shallow-water organisms have a higher capacity to internally buffer changes in pH as compared to deep-sea organisms of similar physiology, leading to a conclusion that injecting $CO_2$ gas may cause disturbances in marine physiology. Furthermore, due to oceanic currents, $CO_2$ that is simply injected into the deep water will be mixed enough so that eventually it can be released back into the atmosphere in a short enough time as to be considered not a permanent option (House, et al. 2006).

Logistical concerns may be encountered with sedimentary injection, one of which is centered around the formation of hydrates. On the one hand, since hydrates are solid, crystalline forms, they can inhibit the ability of the supercritical $CO_2$ to flow into the pore spaces of the substrate. This would require additional energy at the injection point in order to bypass the obstruction created by the formation of the hydrates and may decrease permeability. Since terrestrial $CO_2$ is warmer than the ocean, as it travels down the pipeline to the ocean floor and beyond, heat will transfer through the pipe to the ocean, cooling the $CO_{2.}$ This cooling could depress the temperature enough to cause hydrate formation potentially within the pipe itself, (House, et al. 2006), causing impaction of the pipe and possibly leading to a rupture due to an increase in pressure. Hydrate formation was one factor in the inability to plug the leak in the BP Gulf Oil disaster (BP 2010). On the other hand, if hydrate formation occurs away from the injection point and within the substrate itself, it may generate a “caprock” of its own, thereby enhancing permanency as discussed in geologic formations (House, et al. 2006).

Since both deep-well and deep-sea injection require $CO_2$ to be captured and compressed before sequestration, they are only applicable in cases where the $CO_2$ is coming from a point source. Approximately 38% of all $CO_2$ emissions comes from non-point sources, such as residential fossil fuel use and vehicle emissions, and are known as “air sources” (Davison 2007). (Fig. 2) These non-point sources cannot be captured nor sequestered through the methods discussed and therefore another way must be found to reduce or remove $CO_2$ in these cases. Additionally, all current technological methods used to sequester $CO_2$ require energy, either for compression, transport or injection, making them economically impractical. An RTG requires energy in the form of human labor for the transport of materials and water from the ground to the roof surface, but uses only sunlight to form the biomass in which the $CO_2$ will be sequestered. In addition, RTGs provide benefits that technological sequestration methods do not provide such as food, aesthetic value, heat reduction and storm water management, making an RTG economically viable and environmentally beneficial.

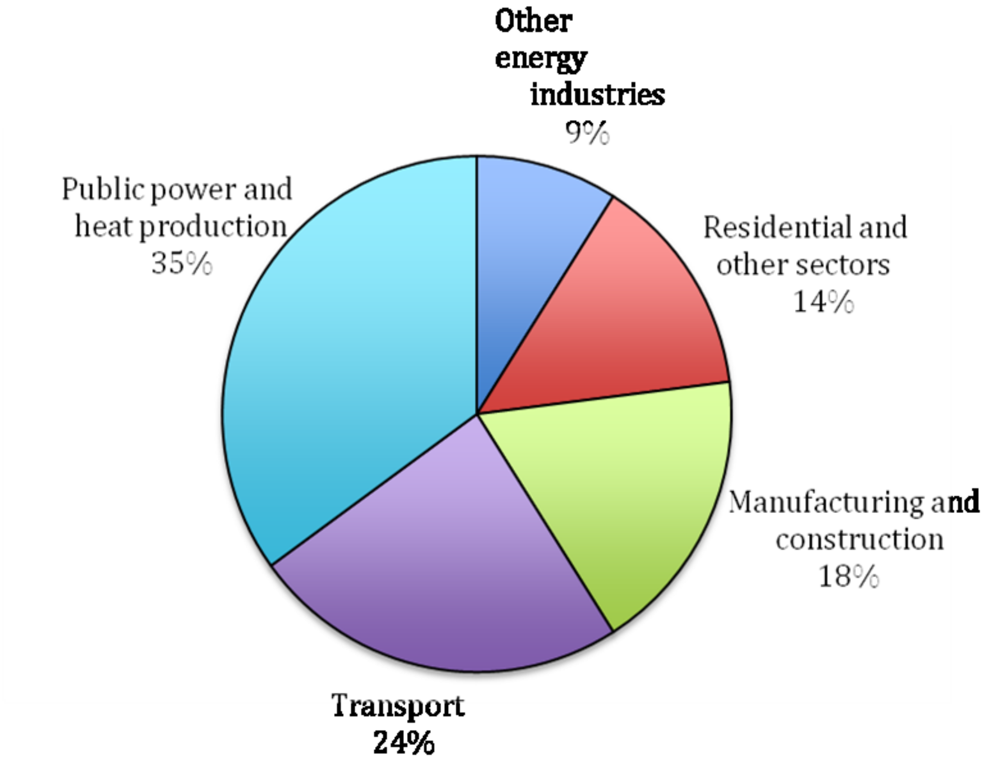


**Figure 2: Emissions of $CO_2$ from fossil fuel combustion, Davison (2007) with permission.**

### 2.1.5. Biomass sequestration

Levels of sequestration can be increased by restoring or improving soil productivity through a change in either agricultural practices or land-use management, but most of the sequestration research to date focuses on soil organic carbon sequestration (Farage, et al. 2007; Upadhyay, et al. 2005). Soil has the potential to store large amounts of carbon but this amount changes based on soil productivity. According to Farage et al., as much as 2200 Pg of carbon is currently stored within the top 1 m of the Earth. Certain agricultural practices can not only reduce this potential, but may also contribute to carbon emissions by releasing the bound carbon into the atmosphere through tillage (Farage, et al. 2007). Research conducted on eroded soils provides a good foundation for discussion as eroded soils hold very little carbon but can be easily amended to increase productivity. For instance, Shi et al. provide a potential progression for soil carbon sequestration based on types of land use, as degraded soil and desertified ecosystems > crop land > grazing lands > forest and permanent cropland (Shi, et al. 2009). They estimate that over the course of 25-50 years, the cumulative potential of carbon sequestration can be as much as 30-60 Pg. This is where green roofs can play an important role in carbon sequestration as a rooftop with no vegetation is akin to completely degraded soil. Since an RTG contains crops, a comparison to cropland, which can aggregate a significant amount of carbon, is appropriate. For instance, in Great Britain (defined as England, Wales and Scotland) non-forested cover such as arable crops and pasture contained 1 X $10^3$ kg C per hectare (approximately 99 g $m^{-2}$) whereas trees ranged from 4.3 to 90.6 x $10^3$ kg C per hectare, depending on tree type (Dawson and Smith 2007). Huotari et al. determined that herbaceous plant biomass in a cut-away peat bog aggregated between 24 g $m^{-2}$ and 118 g $m^{-2}$ of carbon, depending on fertilization (Huotari, et al. 2009). The tree seedling biomass for the same area aggregated between 33 g $m^{-2}$ and 113 g $m^{-2}$. An RTG placed on a non-vegetated roof contains soil for the plants; thus, the potential to increase from zero carbon storage to even 99 g $m^{-2}$ carbon storage is worth consideration. Vegetation sequesters carbon due to the photosynthesis equation:

$$6CO_2 + 12H_2O + \text{light} \rightarrow C_6H_{12}O_6 + 6O_2 + 6H_2O \tag{4}$$

This equation shows us that for every 6 molecules of $CO_2$ used by plants during photosynthesis, 6 atoms of carbon are used to create organic matter in the form of glucose. Thus, a vegetated roof can help to sequester carbon, not only in the soil that the plants are growing in, but also through creation of the carbohydrate molecules that make up plant mass.

While some scientists feel that biomass sequestration has limited capacity (Lackner 2003), many other scientists believe that biomass aggregation is an economically viable way to help sequester atmospheric $CO_2$ . Urban landscapes contain a lot of impermeable surfaces and rooftops can represent a significant portion of that. One study states that rooftops can represent as much as 40-50% of impermeable landscape in an urban environment, which could add up to a potential for large amounts of $CO_2$ sequestration, depending on the size of the urban landscape involved (Rowe 2010). Rowe also states that in mid-Manhattan, impervious surfaces comprise 94% of the total land area. To put this into context, the area of Manhattan is roughly 8700 hectares, ("Area of Manhattan in Hectares") of which approximately 8100 hectares are impermeable surfaces. If even 40% of that is rooftops, that's a potential of just over 3000 hectares that could be converted to a vegetated roof for $CO_2$ sequestration. While it is generally agreed that trees have the largest capacity to sequester $CO_2$, due to the length of time they grow and the amount of biomass they can aggregate, trees cannot be planted everywhere due to urban development and therefore may not necessarily be considered as a complete solution.

In addition to helping to reduce $CO_2$ through photosynthesis, an added benefit is seen in the heat island effect reduction. Since roofs have the same footprint as a building, there is a large amount of "empty" space subjected to sunlight that causes an effect known as the urban heat island. This effect can cause temperatures in cities to be between 6-10° F higher than in areas outside of cities ("The Living Roof "). Measurable differences have been seen by several researchers between an extensive green roof and a conventional roof. Simmons et al. show that maximum green roof temperatures were cooler than conventional roofs by 38°C at rooftop and 18°C inside (Simmons, et al. 2008). Additionally, green roofs had less of a variation in the temperature (less flux) overall, reaching a peak temperature about 1-3 hours later than conventional roofs. Even more significantly, every green roof tested stabilized the temperatures over the course of 24 hours with very little fluctuation. According to the California Academy of Sciences website, approximately 16% of the electricity used in the United States is used for cooling buildings ("The Living Roof"). By maintaining a more even temperature over a 24 hour period, there would be no corresponding spike in energy usage for cooling during the peak daily temperatures, thereby reducing energy demand that could result in reduced emissions from power plants (Rowe 2010). Additionally, plants evapotranspirate and provide shade, both factors in reducing surface temperatures. This reduction in surface temperature has the added effect of decreasing photochemical reactions in the atmosphere, some of which are the mechanisms for the formation of ground-level ozone (Rowe 2010).

Furthermore, researchers noticed that the reduction in heat flux was not just on the rooftop (Oberndorfer, et al. 2007). In some cases, reductions of up to 60% in the floor below the roof were also noticed (Oberndorfer, et al. 2007). Liu and Baskaran also experienced reductions in heat flux, with significant reductions in the spring and summer months. They note that in winter, the temperatures were naturally stabilized on both the reference and the extensive ecoroof due to snow coverage, which provided even insulation (Liu and Baskaran 2005). One could expect a similar effect in Pittsburgh, where the winter months are typically snow-filled.

### 2.1.6. Impact of plant varieties on ecosystem services

Most of the available research used one of several varieties of *Sedum*. *Sedums* have the benefit of forming low, dense mats of vegetation and often crowd out other plants, reducing maintenance. On the one hand, they are drought- and extreme temperature-resistant and so are able to withstand rooftop conditions. On the other hand, their shallow root systems only have limited uptake capability. When planted as a monoculture, they provide a limited ecosystem with low biodiversity (Oberndorfer, et al. 2007).

However, some research has been done on plants other than sedums. Dunnet et al. designed two comparative experiments, with different plant varieties. The first used festuca (a type of grass), rough hawkbit (a type of forb) and several sedge species. The second experiment used the standard sedums, in addition to forbs and grasses (Dunnett, et al. 2008). While the researchers were more interested in whether culture diversity had an impact on runoff and heat reduction, some of their data is relevant to this project. Both experiments used a rainfall simulator attached to the "roof" structure. Rain was simulated in 15 minutes bursts of 2L for heavy rainfall and 1L for a light rainfall. Their results showed that bare soil seemed to have approximately the same runoff rates as the biodiverse mix (Dunnett, et al. 2008). In a garden roof, there are bare spaces used in the walkways and in between plantings. Since bare soil did not increase the amount of runoff in the experimental setups, then walkways or a winterized garden should not have a negative impact on storm or snowmelt runoff.

A second trend noticed in both experiments centers around the height of the plants and the width of the leaves, and the effect this had on water retention. In the first experiment, the researchers found that the forbs reduced runoff more so than did any other group and attributed it to the dense coverage and the flat, broad leaves. They concluded that the leaf surfaces contributed to a higher level of evaporation than what was seen in the thin-bladed grasses (Dunnett, et al. 2008). Most garden crops have broad leaves to aid in photosynthesis during fruiting and maturation and so it would be reasonable to expect a similar rate of evaporation and runoff reduction as seen with forbs. The second experiment's results showed that the least amount of runoff was seen in *A. odoratum*, with a mean height of 18 cm (~7 inches). Many garden crops reach or exceed this height and so would have a greater impact on evaporation rate (potentially further decreasing the heat island effect), water retention and runoff rate.

Furthermore, both of these experiments used trays that were only approximately 6 inches deep at the maximum. Garden crops require deeper substrate in order to maintain optimal growth. As mentioned previously, deeper substrates were associated with an increase in water retention and delay in peak runoff times. By extrapolation, since RTGs would have deeper substrate overall, even if planting in pots, all of the aforementioned benefits would hypothetically be greater in RTGs than in extensive roofing systems.

#### 2.1.7. Design Requirements

Extensive roofs require several layers of construction in order to be maintenance-free. These layers can include all or a few of the following elements: a waterproof membrane, an insulating membrane that may be above or below the waterproof layer, a root barrier, a filter fabric layer, a drainage layer, a water retention layer, growing medium and finally the vegetation (Liu and Baskaran 2005) (Fig. 3). The number and type of layers required depends not only on the roof structure, but also on the intended use of the roof (Gibbons 2009). RTGs have different requirements in terms of structural design as they must have egress for moving soil, fertilizer, planting materials and water. The egress must be such that movement of materials is easily and safely done. RTGs generally do not require any modification to the roofing system as walkways and planters prevent direct contact with the roofing membrane and also provide a barrier against accidental puncture from dropped tools, shoe heels, etc. ("Urban Agriculture Notes" 2003). Municipal code requirements may affect the design of the RTG as some municipalities may restrict plantings due to historical designations and handicap accessibility may also be a factor in the design. Finally, structural support must be assessed to determine if the existing structure can bear the additional weight of the RTG. This assessment is best handled by a structural engineer or architect to ensure that the American Society for Testing and Materials (ASTM) standards are met for code requirements, in addition to any local government building codes (ASTM Standards and Engineering Digital Library). However, a standard guideline used by industry is to keep the weight load at ≤ 50 pounds/sq. ft (Gibbons 2009). In order to minimize weight, a lightweight medium with the appropriate level of nutrients to support growth should be used.

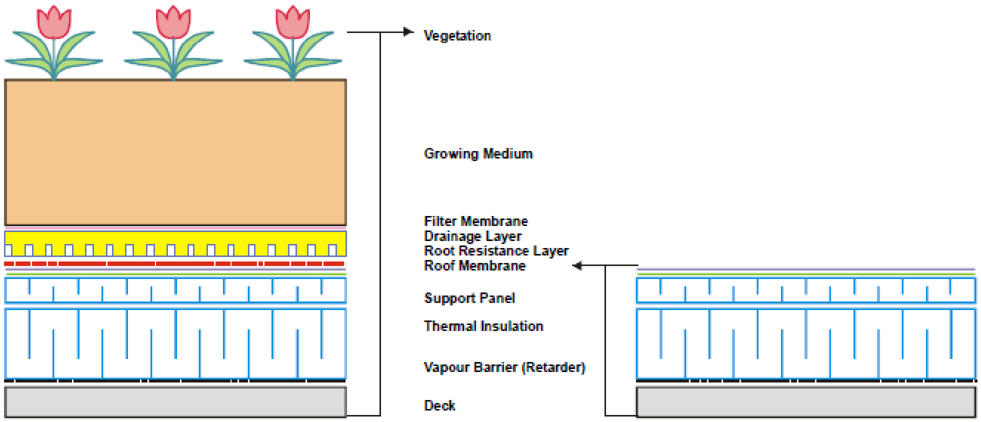


**Figure 3: Schematic of roof designs with a garden (left) and a typical roof design without a garden (right). (Liu and Baskaran, Using Garden Roof Systems to Achieve Sustainable Building Envelopes 2005) Reprinted with permission.**

### 2.1.8. Cost Factors

One of the biggest factors in retrofitting an existing roof into a green roof is cost, with many researchers concluding that intensive roofs are more expensive than extensive roofs (Rowe 2010), (Carter and Keeler 2008). Some of these costs can be reduced by factoring in the return on investment of the roofing system as a vegetated roof increases the lifespan of the roofing membrane due to a more stable temperature over the course of any given year (Liu and Baskaran 2005; Carter and Keeler 2008). Other costs can be reduced or removed by the use of reclaimed or recycled materials or through creative design.

Many large-scale RTGs incorporate a high-tech design with commensurate investment. For instance, one rooftop greenhouse in Montreal required a $2 million investment to build and stock (Woessner 2011). Another example is found in Torre Huerta, Valencia, Spain. This building design incorporates trees on the balconies of the apartments in an effort to reduce air pollution, but carries a €12 million price tag

(Woodward 2011). Few people can afford such an investment but lower tech solutions, coupled with sound agricultural processes, can reduce this cost to such extent as to be affordable by most. For instance, using cardboard boxes, reclaimed lumber, or cast-off items would reduce the cost for structure and supports to very low levels, while starting seeds indoors as opposed to purchasing seedlings would add to that reduction. (Fig. 4)

**Figure 4: Example of creative use of reclaimed materials used to construct an RTG. http://urbangardencasual.com/2009/09/11/rooftop-farms-in-brooklyn-new-york/ Accessed December 5, 2011.**

### 2.1.9. Specific Aims

The specific aims of the research are to determine the potential of RTGs in an urban setting (e.g., Pittsburgh, PA) to reduce local levels of $CO_2$, remediate storm water runoff, and provide boutique vegetables for an eating establishment.

### 2.1.10. Experimental Design

In order to test the hypothesis that urban rooftop gardens can reduce local levels of $CO_2$, remediate storm water runoff, while providing boutique vegetables for an eating establishment, a garden will be grown on the top of a building housing a restaurant located on the South Side of Pittsburgh. Each particular crop will be grown in boxed enclosures. Both fruit and vegetative plant mass will be measured to determine an estimate of $CO_2$ sequestration. The matric potential of the soil will be determined to assess the potential impact RTGs on storm water runoff. The inventory of produce provided to the restaurant will be used assess the contribution of RTGs to the menu.

# Chapter 3 Methods and Materials

### 3.1.1. Research Garden

### 3.1.2. Garden Layout and Design

The footprint of the garden was an area 14’ x 17’ (238 $ft^2$ or 3.16 $m^2$) on which a substructure was to be built. The roof is covered in an asphalt roofing material and is split into two portions. Only one side of the existing roof will be used for the research garden; the other side contained a rain gauge for control data. (Figs. 5-8).

**Figure 5: View of the roof from the parking lot. Access to roof was through lower door (Arrow 1), then up interior steps, through a door, into a conference room, out the window (Arrow 2), up a ladder (Arrow 3), to the control roof. The RTG is on the other side of the small peaked roof (Arrow 4). This picture illustrates why easy access to the roof is essential.**

**Figure 6: Garden roof location, before vegetation, as standing at the edge of the roof above the parking lot. Refer also to Figure 7.**

Standing here for Figure 6.

**Figure 7: Garden roof before vegetation, as standing at the back of the roof looking onto the parking lot.**

**Figure 8: Rain Gauge and bucket on control roof.**

A substructure was built out of reclaimed lumber that had been marked for refuse collection**.** The base was constructed from 4x4 beams while the walking surface was constructed from planks, old boards and random pieces of recycled wood on the beam substructure. (Figs. 9,10). These boards also provided the floor space for the planting boxes to sit on.

**Figure 9: 4 x 4 beams as foundation.**

**Figure 10: The base structure.**

### 3.1.3. Planting Boxes

Two basic box designs were used, with both employing repurposed cardboard boxes and black plastic garbage bags. The repurposed cardboard boxes came from the restaurant itself and consisted of produce delivery boxes, wine and beer cases, milk crates, and boxes that had held reams of paper. While this complicated the research by including boxes of various sizes, in addition to different material components, it was better suited to the various plants that were to be grown. Regardless of size, planting boxes were built by one of two methods.

In the first method, a black garbage bag was placed inside the box and wrapped around the outside of the box. The bag was taped down at the bottom on the outside and the excess was removed. The box was then set on top of a drainage board, which was constructed by drilling holes through a piece of reclaimed fiberboard and with brackets attached to each corner to provide elevation, and a second bag was placed over drainage board and box. A corner of the bag was positioned so as to be hanging vertically towards the lowest point so as to enhance the water drainage by utilizing gravity, with the rest of the bag taped to folded down portion of bag #1. One inch diameter tubing (obtained from a local home improvement center) was cut to approximately a 2” length to be used as a rain catcher unit. A corner of the second bag was placed into the tube and duct taped along the join. Then the corner of the bag was cut and taped on inside of tube. A common rubber stopper (as used in utility sinks) was placed inside the tube to form a seal. Once the unit was constructed, the box was filled with soil mix and planted. These rain catcher (RC) boxes also had a layer of black plastic (excess garbage bag remains) placed on top of the soil and around the planting to help deter evaporation. (Figs. 11, 12)

**Figure 11: Interior of planting box, made by 2-bag method. First bag was placed inside the box, drainage holes were punched through both bag and box, excess wrapped around outside.**

**Figure 12: Exterior of same box, showing second bag taped to outside of first with RC attached at bottom.**

The second method also used a drainage board as described above, but only one garbage bag. Here, the drainage board was placed inside the garbage bag and fixed as described above for the rain catcher. The box was then placed inside the bag and on top of the drainage board with the excess bag pulled up and tucked inside the box. The soil mixture was placed on top of the tucked down plastic bag and planted. This also received a black plastic topper made from scraps as described previously. (Figs. 13, 14)

**Figure 13: Interior of planting box, made by 1-bag method. Box has been placed on drainage board (not in photo) and both were placed inside the bag. The top of the bag is tucked inside the box.**

**Figure 14: Exterior of planting box, above, showing rain catcher placement.**

Eight planting boxes, plus one control box, were fitted with rain catchers and placed on top of milk crates to facilitate draining. The remainder of the boxes were built in one of the two methods, but without an RC device.

**Figure 15: View, as standing on peaked transition roof, of the planted garden on June 15, 2011.**

### 3.1.4. Soil Mix

The planting soil used was created by mixing peat moss and cow manure (both purchased in packaged form from the local home improvement center) in a 5:3 ratio. The peat and manure were mixed from the package into a mixing bin, then hydrated with water until the mix was thoroughly damp. Miracle-Gro Shake ‘n Feed Continuous Release All Purpose Plant Food was mixed in according to package directions before filling the planter boxes. Miracle-Gro Water Soluble All Purpose Plant Food was added weekly from June through July and in August, Miracle-Gro Plant Food Spikes were inserted into the planters.

### 3.1.5. Plants

In mid-March, seeds were started in cardboard egg containers using the soil mix as the starting medium. Once they sprouted and the cotyledon formed, the seedlings were placed under grow lights. Unfortunately, approximately 6 weeks into the growing phase, the seedlings became infected by a fungus and the majority of them died. As a result, the research garden was planted with purchased seedlings at the proper time for planting. The final garden layout is shown in Figure 16, with varieties and abbreviations specified in Table 2.

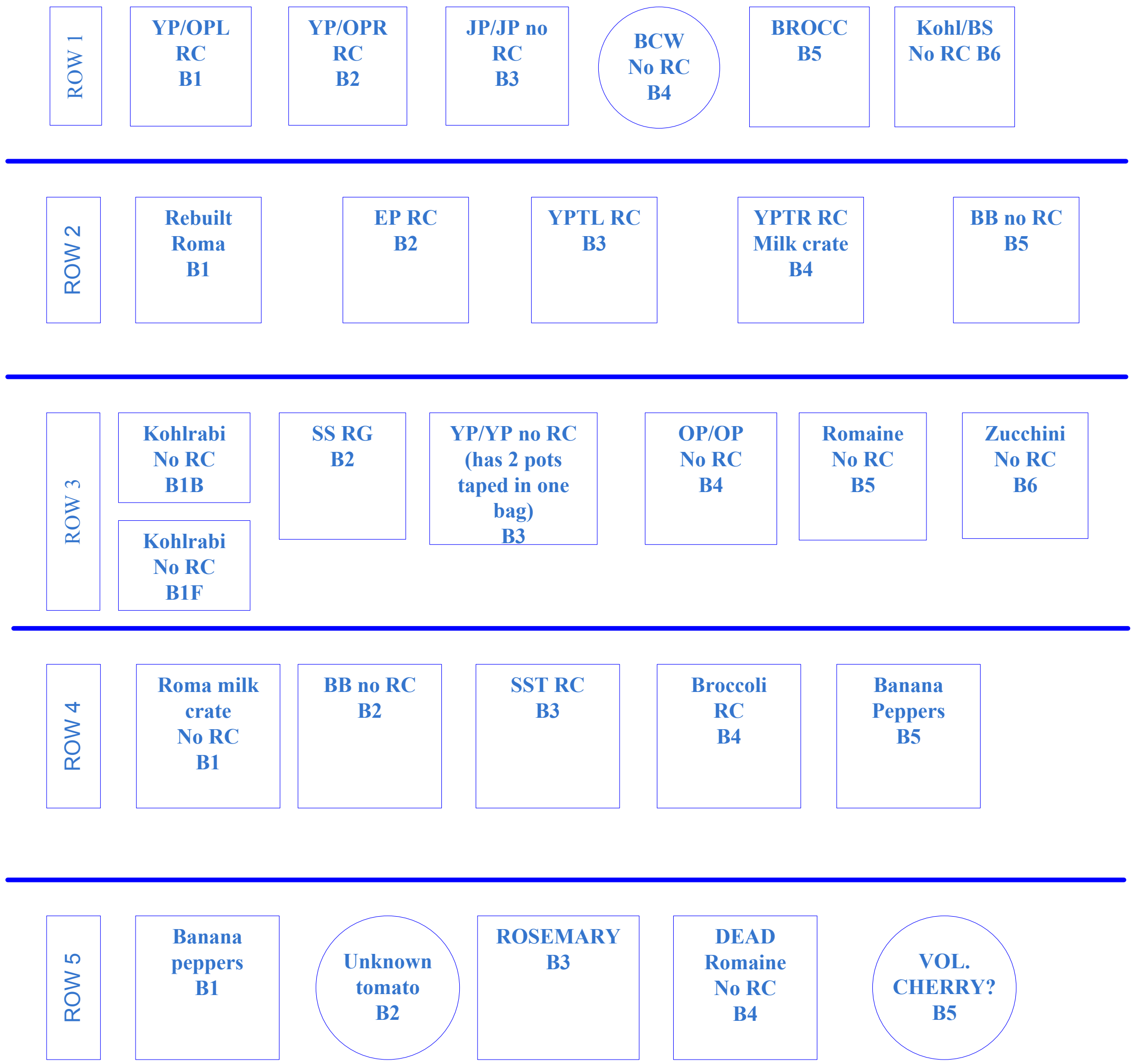


**Figure 16: Diagram of planting layout. The Unknown Tomato in Row 5 was identified, once fruit was set, as a Siberian tomato variety when compared to researcher's personal urban, land-based garden. The tomato at the end of Row 5 was confirmed as a cherry tomato by the same observational process. BCW, SIBER and VC were the only three plants that survived the fungus at seedling stage. All three were from seed that had been saved by researcher from the previous year's urban garden.**

**Table 2: All plants, except for VC, SIBER and BCW, were purchased from the local garden center in early May, 2011.**

| Variety | # of plants | Abbreviations |
|---|---|---|
| Orange Bell Pepper | 2 | OP |
| Yellow Bell Pepper | 2 | YP |
| Romaine Lettuce | 6 | ROMAINE |
| Jalapeno Pepper | 2 | JP |
| Volunteer Cherry | 1 | VC |
| Purple Kohlrabi | 6 | KOHL |
| Sweet Banana Pepper | 4 | BP |
| Brussels Sprouts (*Bubbles*) | 6 | BS |
| Tomato (*Better Boy*) | 2 | BB |
| Tomato (*Roma* ) | 2 | ROMA |
| Tomato (*Supersonic*) | 2 | SS |
| Eggplant (*Ichiban Egg* Japanese eggplant) | 2 | EP |
| Rosemary (*Rosmarinus officianlis)* | 1 | RM |
| Tomato (*Yellow Pear* tomato, heirloom) | 2 | YPT |
| Tomato (*Box Car Willie*, heirloom) | 1 | BCW |
| Tomato (*Siberian*, heirloom) | 1 | SIBER |
| Total Plants | 42 | |

### 3.1.6. Garden maintenance

Growing plants require water at regular intervals and, while it had been hoped rainfall would be sufficient to sustain the plants, this proved to not be the case. Therefore, supplemental watering was carried out whenever necessary. Since the garden roof was not accessible on several days each week, supplemental watering was sporadically carried out by the chef, Steve Lanzilotta. As such, not all watering amounts were captured and measured. Two basic models were followed for watering of the garden and both involved the garden hose; one method used a milk jug to measure and the other used the touch test.

For the first method of watering, a gallon milk jug was used as the measuring scale as that is a standardized unit of measure (USDA 1992) (1 gal = 3.78L). (Fig. 17) Watering in this manner was done as needed with varying amounts of water added to each box. (Table 3) This was the method used by the researcher. The second method was used by the chef during the days the researcher did not have access. In this method, the chef placed the hose nozzle in the box and moved it around until the box felt saturated to the touch. After saturating all boxes, waster was released from the hose, with the nozzle pointing upward, in order to simulate rain. The RTG was watered in this manner on various days and for various lengths of time, neither of which was measured.

**Figure 17: Standard milk jug used for watering. The handwritten lines were approximations of fluid volume as measured by a graduated cylinder.**

**Table 3: Volume of water input as supplemental watering. Totals are volume in minus volume drained. The control box (CB) was not operational until the end of July.**

| Date | R1B1 | R1B2 | R2B1 | R2B2 | R2B3 | R2B4 | R4B3 | R4B4 | CB | TOTALS (ml) | TOTALS (gal) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 6/14/11 | 1500 | 4500 | 1500 | 1500 | 950 | 3000 | 3000 | 3000 | | 18950 | 5 |
| 6/22/11 | 2500 | 2500 | 1500 | 2498 | 1500 | 3960 | 0 | 850 | | 15308 | 4 |
| 6/28/11 | 3595 | 3785 | 500 | 7571 | 3785 | 3785 | 3785 | 4785 | | 31593 | 8 |
| 6/29/11 | 3670 | 2608 | 3785 | 0 | 2135 | 2635 | 3728 | 3398 | | 21960 | 6 |
| 7/6/11 | 1885 | 1890 | 1883 | 2839 | 1508 | 1893 | 3785 | 3785 | | 19468 | 5 |
| 7/11/11 | 3685 | 3510 | 7571 | 7571 | 2860 | 3680 | 3290 | 3488 | | 35657 | 9 |
| 7/13/11 | 3323 | 2834 | 3785 | 3775 | 2816 | 3753 | 3785 | 3010 | | 27083 | 7 |
| 7/21/11 | 3765 | 3525 | 3785 | 3785 | 2603 | 3685 | 3665 | 3640 | 1498 | 29953 | 8 |
| 7/22/11 | 7571 | 7276 | 3780 | 3785 | 3095 | 3785 | 3784 | 3105 | 3215 | 39398 | 10 |
| 7/26/11 | 3780 | 3745 | 3785 | 3785 | 2255 | 3410 | 3785 | 7571 | 1668 | 33786 | 9 |
| 8/29/11 | 4868 | 3385 | 3785 | 7461 | 2745 | 3780 | 3785 | 0 | 3390 | 33201 | 9 |
| 8/31/11 | 3180 | 3010 | 3785 | 3780 | 2505 | 3784 | 5678 | 0 | 3380 | 29105 | 8 |

### 3.1.7. Lab Procedures

### 3.1.8. Water Data

Data for both watering and rain events for the boxes was collected in the field by removing the stoppers from the RCs and allowing captured water to flow into containers. The effluent was then measured by pouring into a graduated cylinder. In the case of watering events, the stoppers were removed from the RCs and containers placed under the tubing prior to the start of watering, which remained in place until all boxes had received water (approximately 1 hour). After all boxes were watered, the effluent was measured with a graduated cylinder.

Data from the buckets and rain gauges (RGs) was collected slightly differently. Since both buckets and RGs had open tops and were placed in areas without vegetation, the rain was simply collected and then carefully poured into a graduated cylinder for measuring. All buckets had bricks placed into the bottom to anchor them against windy conditions. RGs were set up near the buckets by placing the pointed end in between bricks to anchor against wind. On several occasions, the buckets were blown over by high winds and data was unable to be collected. As such, all bucket data has been removed from calculations and only RG data was used to calculate amount of precipitation in comparison with published rain data.

The calculations to determine absorbency required several preliminary calculations to determine total volume absorbed. Theoretical values for gallons of rain that fell were determined first by using the conversion factor of 1 inch of rain = 600 gallons in a 1000 $ft^2$ catchment area and applying it to the area of the RTG footprint. ("How Much Water Can You Collect In Rain Barrels During a Rainfall?" 2010) This conversion factor was multiplied by the percent of the RTG that was covered by the RCs to determine the theoretical volume of rain that fell in the RCs if 1 inch of rain were to fall. Since less than 1 inch of rain fell during most rain events, the inches collected from the RGs were averaged and then multiplied by the volume that fell in the RCS, the result of which is the theoretical volume of rain that fell in the RC boxes.

The volume of rain outflow from the RC boxes that had been collected and measured was converted to gallons and these amounts were summed across individual rain events for all the RCs. The total outflow was subtracted from the theoretical volume and the result was divided by the theoretical volume to determine the volume that was absorbed by the RCs.

Absorbency was calculated by dividing the total volume that was absorbed by all of the RC boxes by how much fell into the RC boxes for each rain event and then averaged.

### 3.1.9. Biomass Data

As the produce matured, it was picked and each unit of produce was identified by row and box number with a decimal to note how many from each plant. (Fig. 18). The produce was then transported to the lab to be weighed on a Mettler BasBal BB 2400 (lab scale) and also on a Royal Model ds5 scale (field scale).The field scale was accurate to ± 1 g, but this proved to be not entirely true at lower unit weights. The Mettler scale is accurate to ± 0.01 g . The field scale would be used by the chef to weigh harvested produce while the researcher was out of the country.

**Figure 18: Example of produce that was labeled in the field prior to weighing.**

After weighing, the produce was loaded onto a residential dehydrator (Nesco Snackmaster Encore Model FD-61) and dried according to manufacturer recommendations. Each unit of produce was placed on the dehydrator and labeled to avoid confusion. (Fig. 19) After full dehydration (tested by crumbling), the units and labels were removed and each unit individually packaged in plastic to prevent absorption of moisture until it could be transported back to the lab. (Fig. 20) Once back in the lab, each unit was individually weighed on both the field scale and the Mettler scale to ensure accuracy.

**Figure 19: Example of labeling on dehydrator when produce is first placed on it. The paper labels would be added to the dried packets to retain proper identity. Several tomatoes in the foreground had blossom rot and this contributed to the inability to use linear regression for dried weight forecasting for this variety. (See Results section).**

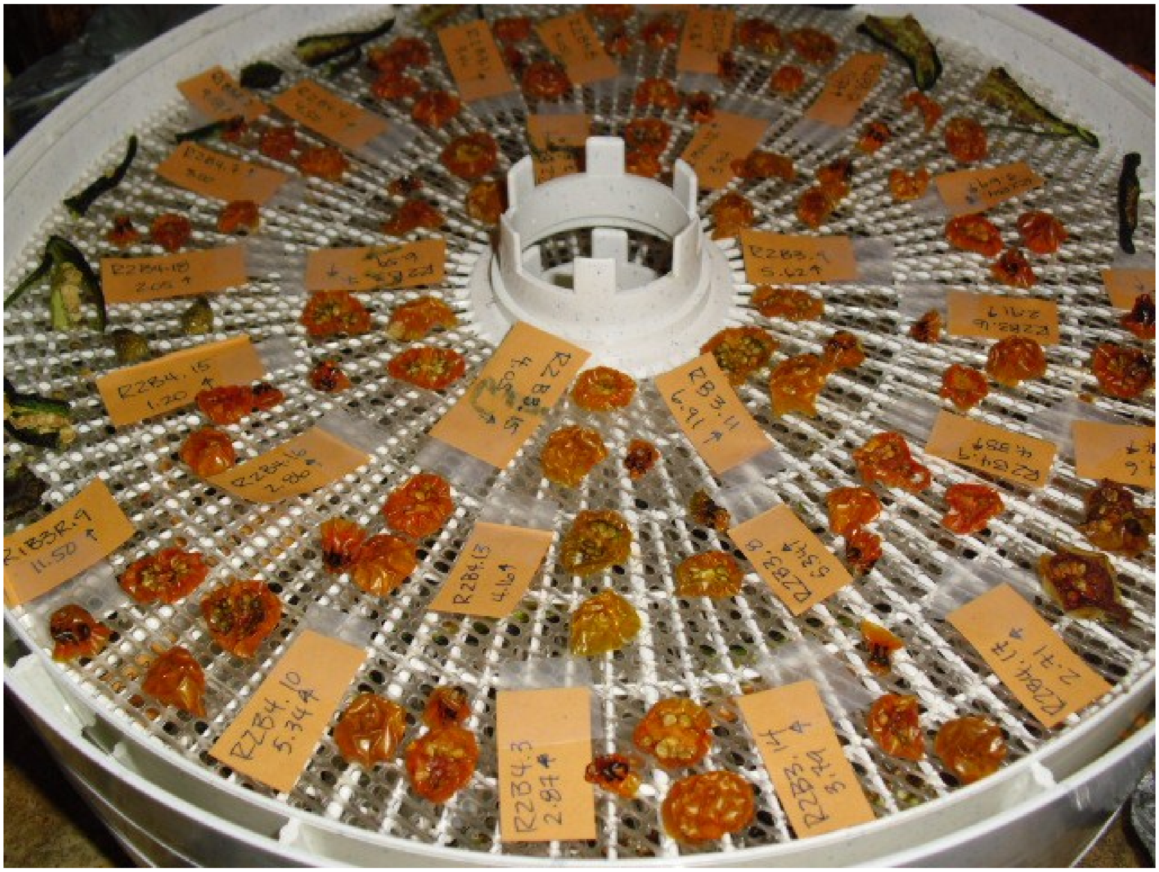


Figure 20: Produce after full dehydration.

An additional step was taken with the yellow pear and cherry tomatoes. Each of these fruits had circumference measured by wrapping a ¼” wide piece of paper towel around the middle. This was done in order to make a bin for counting purposes, as the researcher would be out of the country during part of the harvest. (Figs. 21, 22). The chef was then able to simply separate tomatoes by circumference and count how many of each size he obtained. Larger produce was weighed on the field scale during this time. The produce harvested by the chef was used in the restaurant and therefore no dried weights were obtained. At the end of the growing season, all above-ground biomass was collected, weighed, and dehydrated as discussed.

Figure 21: Bin used to count number of YPT harvested by chef.

Figure 22: Bin used to count number of VC as harvested by chef.

### 3.1.10. Soil matric potential (SMP)

In order to determine the level of saturation in the soil used in the field, two sets of lab experiments were conducted, with both sets utilizing a sample of soil from the field. At the end of the experimental season, sample soil was obtained by removing random volumes from each planting box. Once all boxes had been sampled, the soil was thoroughly mixed to ensure a representative sample was made. This sample was then stored in an unheated garage (temperature ranges 26° to 63°F) for approximately 6 weeks until the lab experiments were run (Pennsylvania State Climatologist 2011). The sample was not homogenized in any way, thus lumps, sticks, root hairs from plants, and other debris were present in the first sample in order to closely mimic field conditions. The second saturation study ("homogenized") used the same soil, but debris had been removed and the soil was dried for 24 hours at 155° F using the Nesco dehydrator.

For the first saturation study, a tared, graduated cylinder was weighed empty. Dry dirt was placed in it to an approximate volume of 250 mL and the cylinder was weighed again and the difference was calculated. This value became $m_{dry}$. The cylinder was filled with water slowly, allowing it to percolate through and be absorbed. Once water was seen to be standing of the surface of the soil, no more water was added. The volume of water poured in was noted, as was the volume of water poured off the surface and the difference calculated. The cylinder was weighed once again, the calculated being $m_{wet}$. Three additional trials were conducted, but in this case, approximately 100 g of the soil sample was used and the volume was noted.

For the homogenized sample, the protocol was similar as above, but some changes had to be made in the process due to the differing nature of the soil used. Peat moss was chosen as the base for the soil mix for two reasons: 1) it is used in the majority of commercial seed-starting, potting and garden soil mixes and 2) it has a high absorbency factor. However, in order for peat to become fully absorbent, it must be hydrated prior to use, and requires hand mixing during the hydration process. This process was used in the field, but to simulate it in the lab, the saturation protocol was adapted.

The tared cylinder was weighed empty, then filled to an approximate volume of 250 mL with the dehydrated sample. The cylinder was weighed again and the difference was calculated and noted as $m_{dry}$. For this set of trials, a measured amount of water (250 mL) was poured into the cylinder and allowed to sit for 10 minutes, with occasional stirring to ensure even distribution of water. After 10 minutes, another 100 mL of water was poured in, stirred once and allowed to sit for another 10 minutes. A filter paper was placed in a funnel on top of a graduated cylinder and excess water from the soil-filled cylinder was slowly poured out over the filter until all standing water drained out. Excess soil that accumulated on the filter paper was scraped back into the soil cylinder. The drained cylinder was then weighed wet, the difference calculated and this valued labeled as $m_{wet.}$ Soil matric potential calculations were performed on both trials using the equations shown below, where $\theta_g$ is the gravimetric volume (the mass of water per mass of dry soil); $\theta_v$ is the volumetric water content (volume of liquid per volume of soil); and $\varepsilon$ is the soil porosity, which defines the maximum possible volumetric water content. Soil porosity indicates the amount of stored water in a soil profile (Bilskie 2001).

$$\theta_g = m_{wet} - m_{dry}/m_{dry} \qquad (1)$$

$$\theta_v = \theta_g(m_{dry}/v_{soil}) \qquad (2)$$

$$\varepsilon=1-((m_{dry}/\text{soil volume})/2.6\ \text{g/cm}^3) \qquad (3)$$

Ideally, the boxes should have been weighed empty and dry, filled with mix, at saturation point, but this was not practical in the field. Therefore, overall soil absorbency was determined through calculations. The first units to be determined were $m_{wet}$ and $m_{dry}$ and both were calculated in similar fashion, using the average weight of the grab sample trials. The average $m_{dry}$ was shown to be 91.5 g and this was multiplied by individual box volumes. The result was then divided by the average volume of soil in the graduated cylinders. For $m_{wet}$, the average value from the laboratory trials was 207.25 g.

# Chapter 4 Results

### 4.1.1. Storm Water Management

The soil porosity of the mix was established to be 0.86, which indicates that at maximum saturation, the soil can hold 86% of its volume in water. This porosity was seen in both soil saturation studies, in addition to being observed on the RTG. The gravimetric volume was calculated to be 0.44, indicating that just over half of the pore space is filled with water at maximum saturation. The soil mixture had a 96% absorbency. If the soil mix was completely dry, water was not easily absorbed and much of it ran off of the surface of the soil. Conversely, if the soil mix contained some level of moisture prior to a rain event, then water was more completely absorbed. This had implications for retention as there were several occasions when there was little precipitation or supplemental watering, due to inability to access the RTG. (Fig. 23, 24)

The garden roof footprint was 238 ft$^2$, with 14% of it being covered by vegetated boxes and 5% covered by RCs. Rain was measured for the period from 6/15/2011 through 9/9/2011 with a total of 7 inches being recorded during that time. This translated into approximately 143 gallons that were captured in all the planter boxes, with approximately 55 gallons captured in the RCs, of which 54.12 gallons were absorbed. Supplemental watering was given on days when rainfall was not adequate to keep the plants healthy and averaged 1 day between rain or watering events. (Figs. 23, 24)

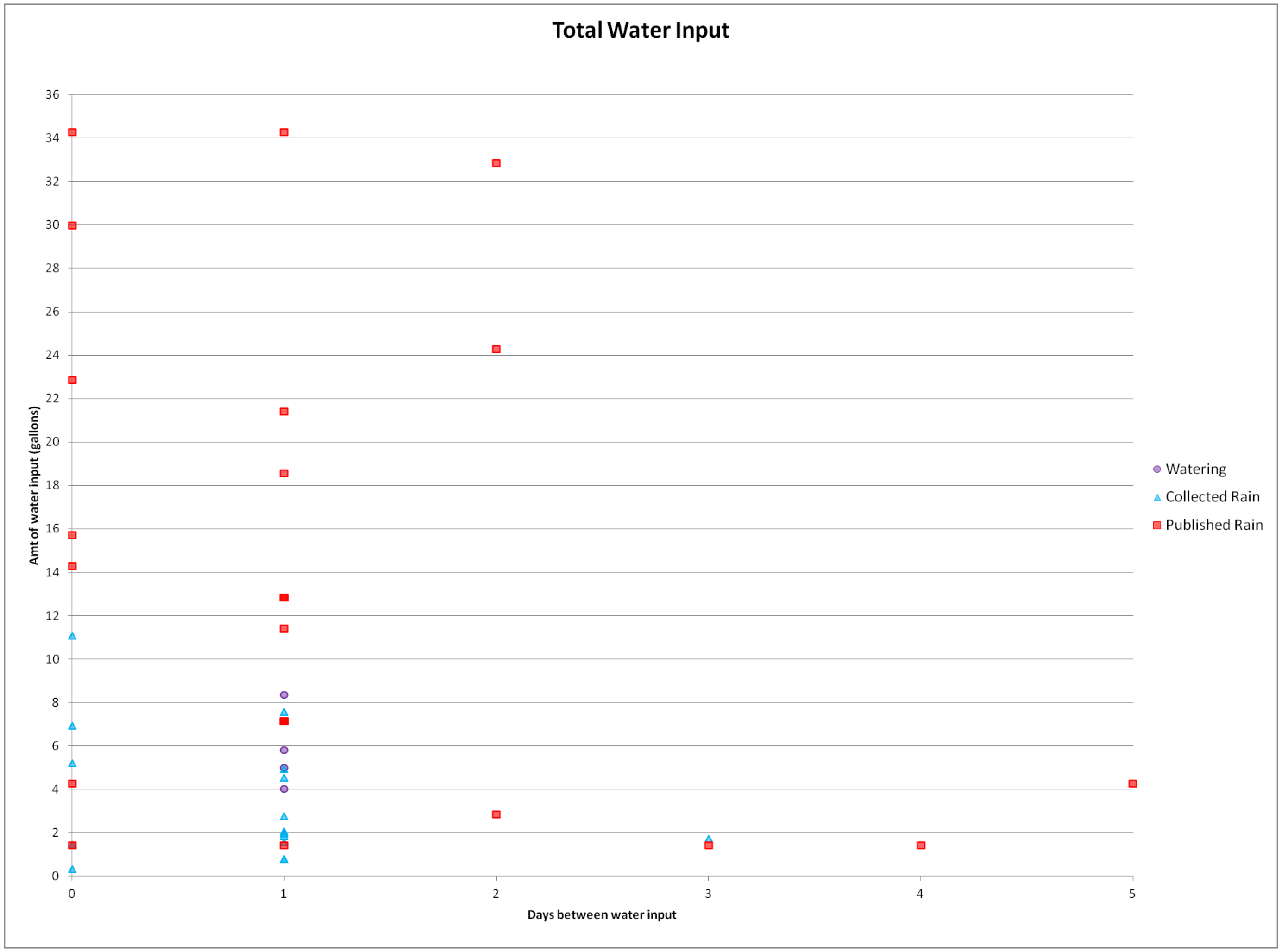


**Figure 23:** Plot of volume of water inputs through rain or supplemental watering. Published rain data was obtained from the Pennsylvania State Climatologist website for comparison (Pennsylvania Climatologist 2011). Rain data points above 50 gallons were omitted from this graph for ease of viewing. http://climate.met.psu.edu/www_prod

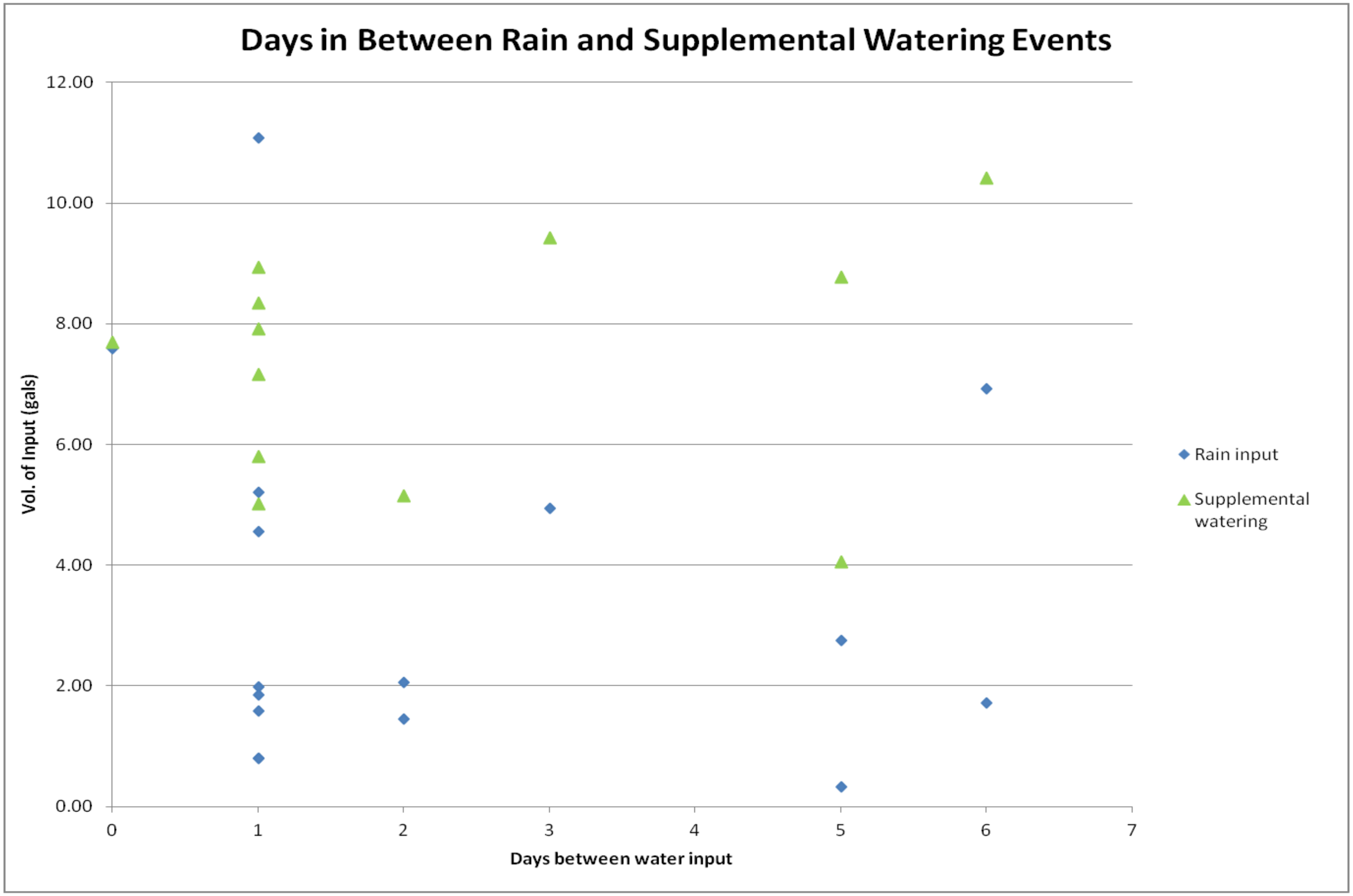


**Figure 24: Days between supplemental watering and recorded rain and does not include published rain data.**

### 4.1.2. Biomass data

For two of the tomato varieties grown, linear regression was used to predict the wet and dry masses of produce harvested by the restaurant. The restaurant used the field scale to weigh larger produce, and the bin process for volunteer cherry tomatoes (VC) and yellow pear tomatoes (YPT). Linear regression for the VC and YPT was based on measured values of research weights for Wet and Dry weight. For all other produce, Correlation and Forecast in Excel, based on Lab Dry to Field Wet weights, was used. If the restaurant did not harvest a particular variety, all reported masses were determined by researcher for both wet and dry mass. All values given are rounded up to the nearest appropriate decimal. The correlation coefficient “r” was used to assess the linear correlation between the wet and dry masses, in addition to between the bin sizes and wet mass. The $R^2$ values were used to determine the percent of variation in the predicted values that can be explained by the linear association between the two values.

The r value for VC was 0.95 and 0.94 for wet and dry weight, respectively. The $R^2$ values, in the same order, are 0.91 and 0.88. The wet weight for VC was a total of 290.45 g, of which 187.45 was predicted with linear regression. The dry weight for VC was a total of 37.72 g, of which 23.87 g was calculated through linear regression. (Figs. 25, 26)

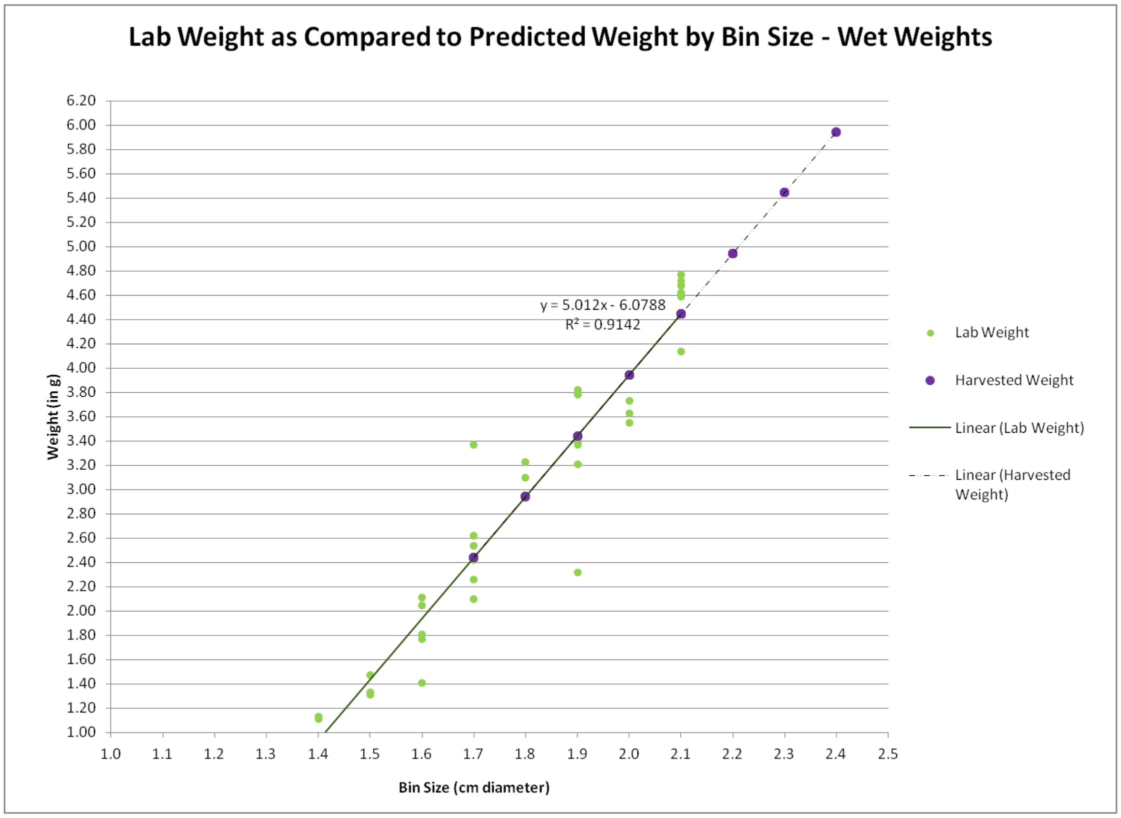


**Figure 25: This graph shows the relationship between the measured lab weights and the predicted harvested weights of VC, based on bin size.**

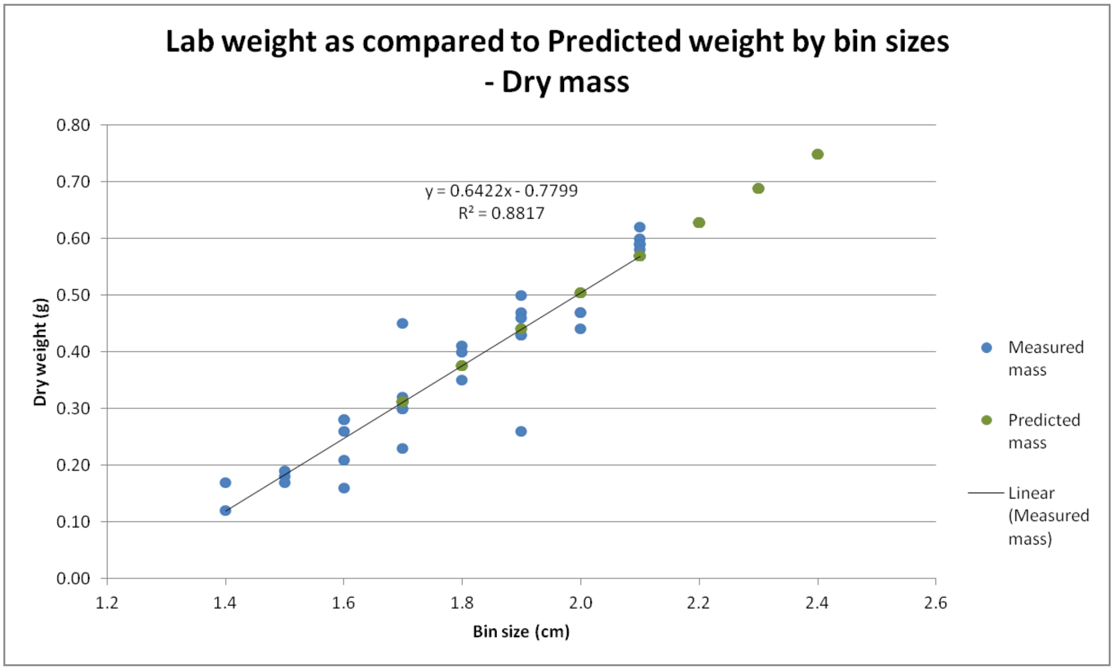


**Figure 26: Compares measured mass of research VC with predicted mass of harvested VC.**

The r value for the YPT was 0.81 wet weight, and 0.76 dry weight. The $R^2$ values, in the same order, are 0.65 and 0.57. The total wet weight for YPT was 859.54 g, with 220.02 g being calculated through linear regression. The dry weight for YPT was a total of 121.29 g, of which 32.09 g was calculated through linear regression. (Figs. 27, 28) Since YPT are shaped like tiny pears, with a narrow neck and fat bottom, they had variance in their weight. As such, the r and $R^2$ values reflected this variance. However, those values were robust enough to warrant usage of linear regression in predicting wet and dry weights for the tomatoes harvested by the chef.

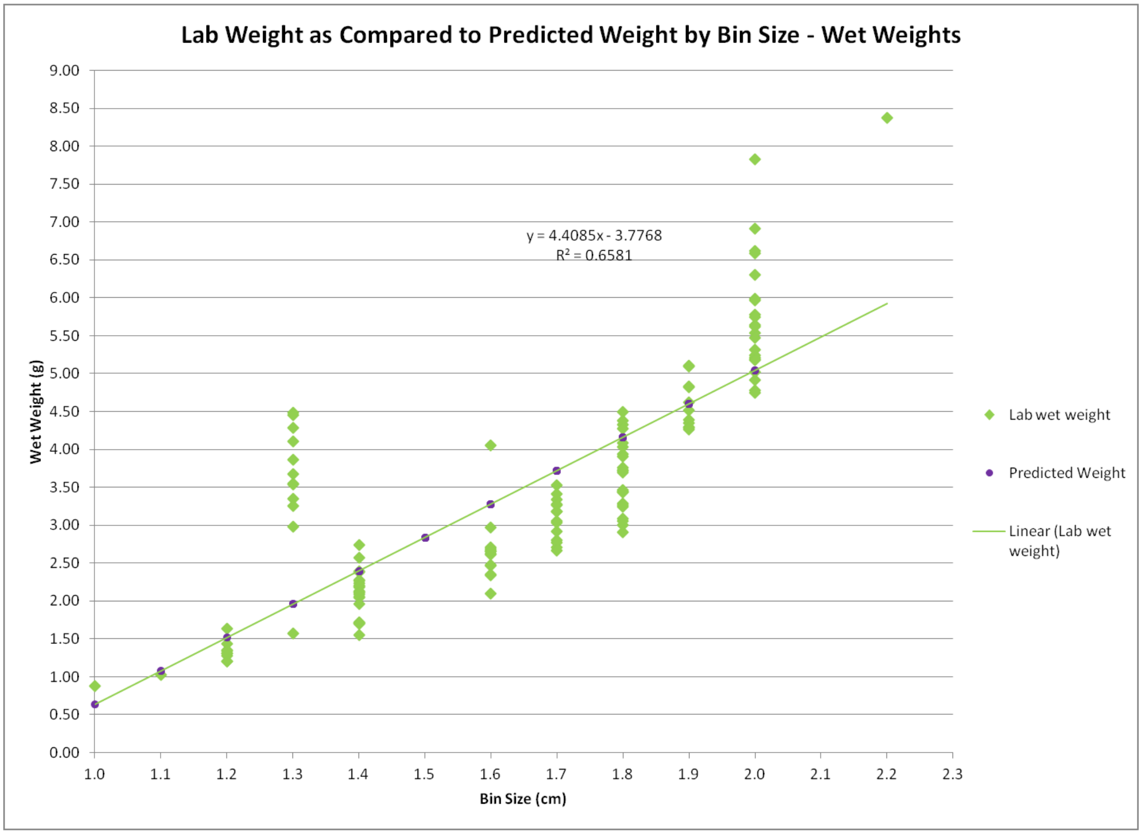


**Figure 27: YPT weight comparison. This shows the correlation between the measured wet weights and the predicted wet weights.**

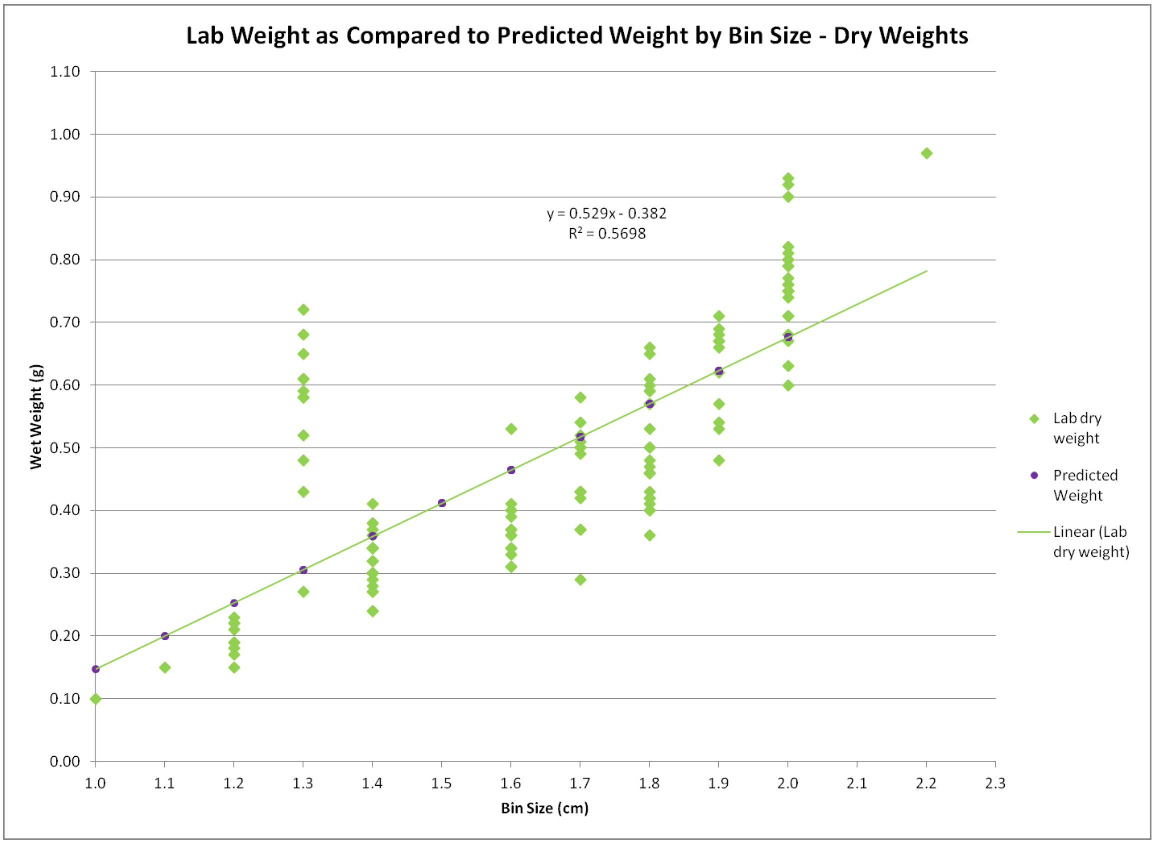


**Figure 28: YPT linear regression of measured dry weight as compared to the predicted dry weight for harvested YPT.**

The r value for Better Boy (BB) tomatoes was 0.85, with a corresponding $R^2$ value of 0.72. These values were determined by comparing the wet and the dry weights. The total wet weight was 2237.59 g, of which 922 g was weighed by the restaurant. The total dry weight was 191.39 g, of which 76.78 g was predicted through Excel. (Fig. 29)

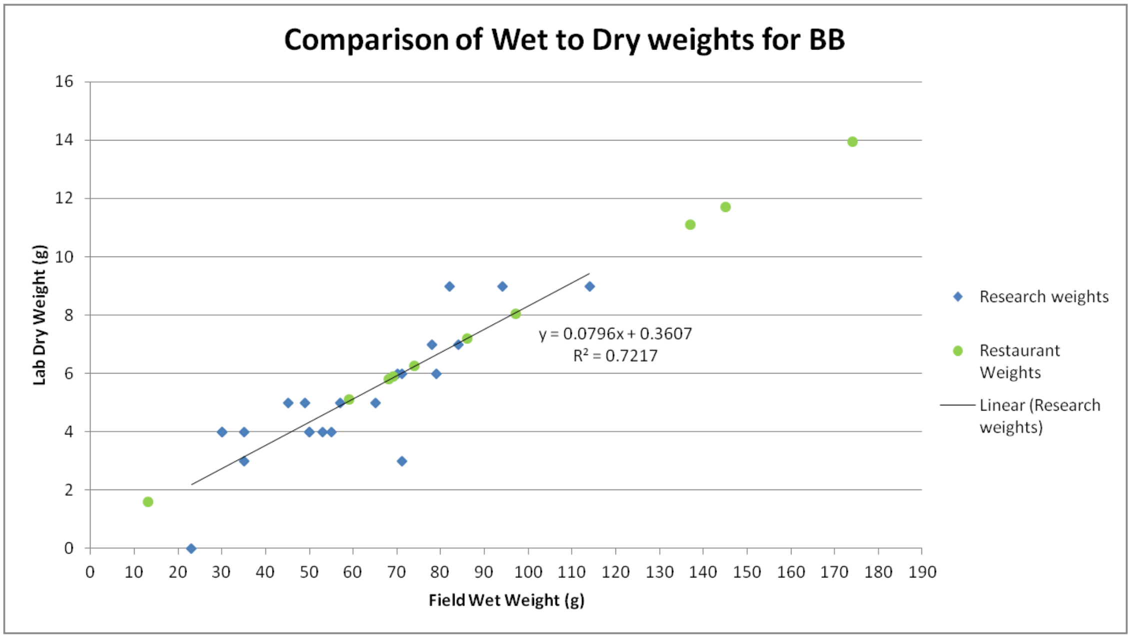


**Figure 29: Wet to Dry mass for BB. Field scale was used for wet weights and lab scale was used for dry. Restaurant weights were predicted based on wet field scale weights to dry lab scale weights in Excel.**

The r value for Box Car Willie tomato (BCW) was 0.97 with a corresponding $R^2$ value of 0.94. These were also determined by comparing the wet and the dry weights. The total wet weight was 595.28 g, of which 266 g was weighed by the restaurant. The total dry weight was 55.13 g, of which 22.5 g was predicted through Excel. (Fig. 30) BCW was not a very productive plant, likely due to an inappropriately-sized container, and therefore the data set is extremely small (n=4).

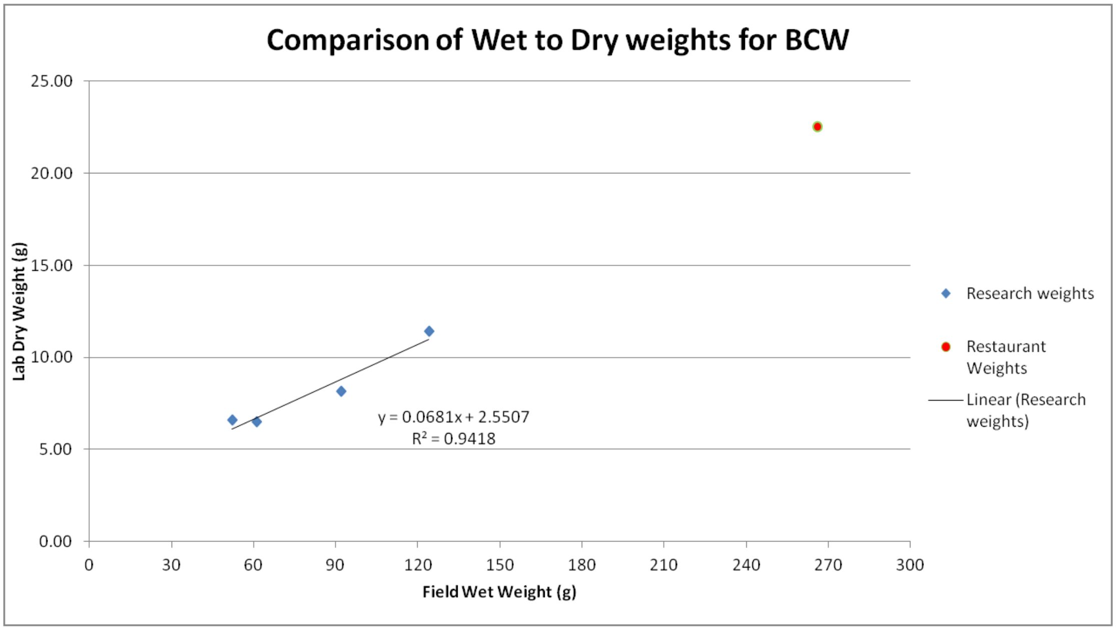


**Figure 30: Wet to Dry mass for BCW. Field scale was used for wet weights and lab scale was used for dry. Restaurant weights were predicted based on wet field scale weights to dry lab scale weights in Excel. This was not a highly productive plant and therefore the sample size is very small.**

The r value for eggplants (EP) was 0.96 with a corresponding $R^2$ value of 0.98. The total wet weight was 2665.81 g, of which 135 g was weighed by the restaurant. The total dry weight was 253.23 g, of which 13 g was predicted through Excel. (Fig. 31)

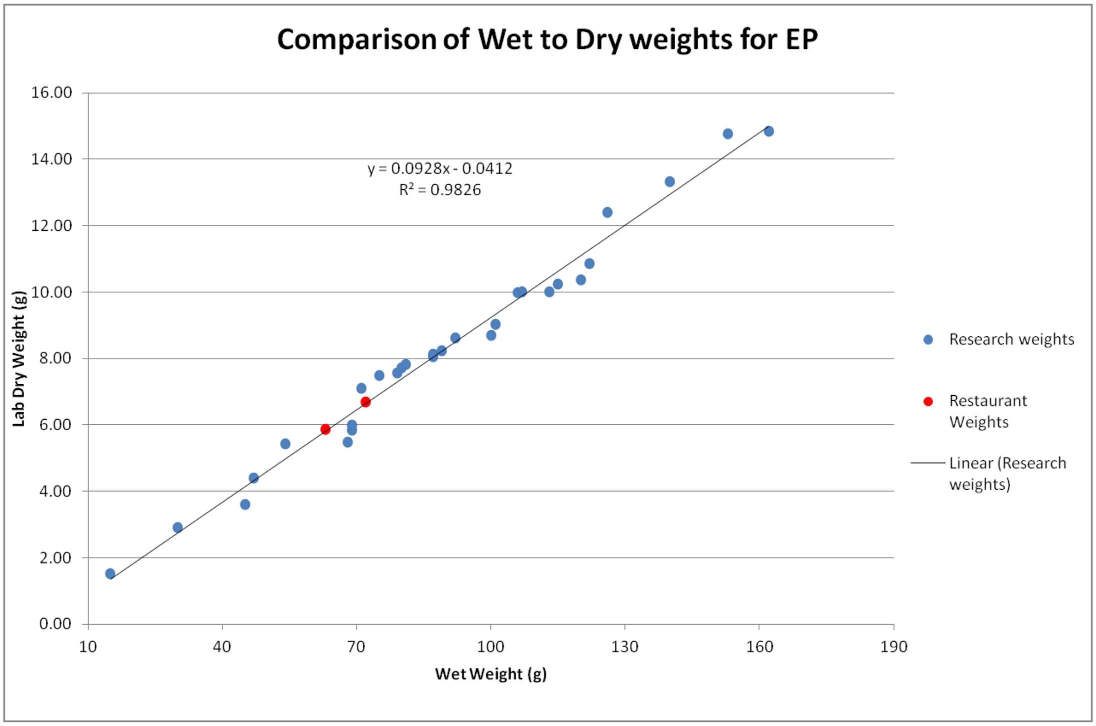


**Figure 31: Wet to Dry mass for EP. Field scale was used for wet weights and lab scale was used for dry. Restaurant weights were predicted based on wet field scale weights to dry lab scale weights in Excel.**

The r value for jalapeno peppers (JP) was 0.94 with a corresponding $R^2$ value of 0.88. The total wet weight was 1299.39 g, of which 425 g was weighed by the restaurant. The total dry weight was 115.14 g, of which 37.40 g was predicted through Excel. (Fig. 32)

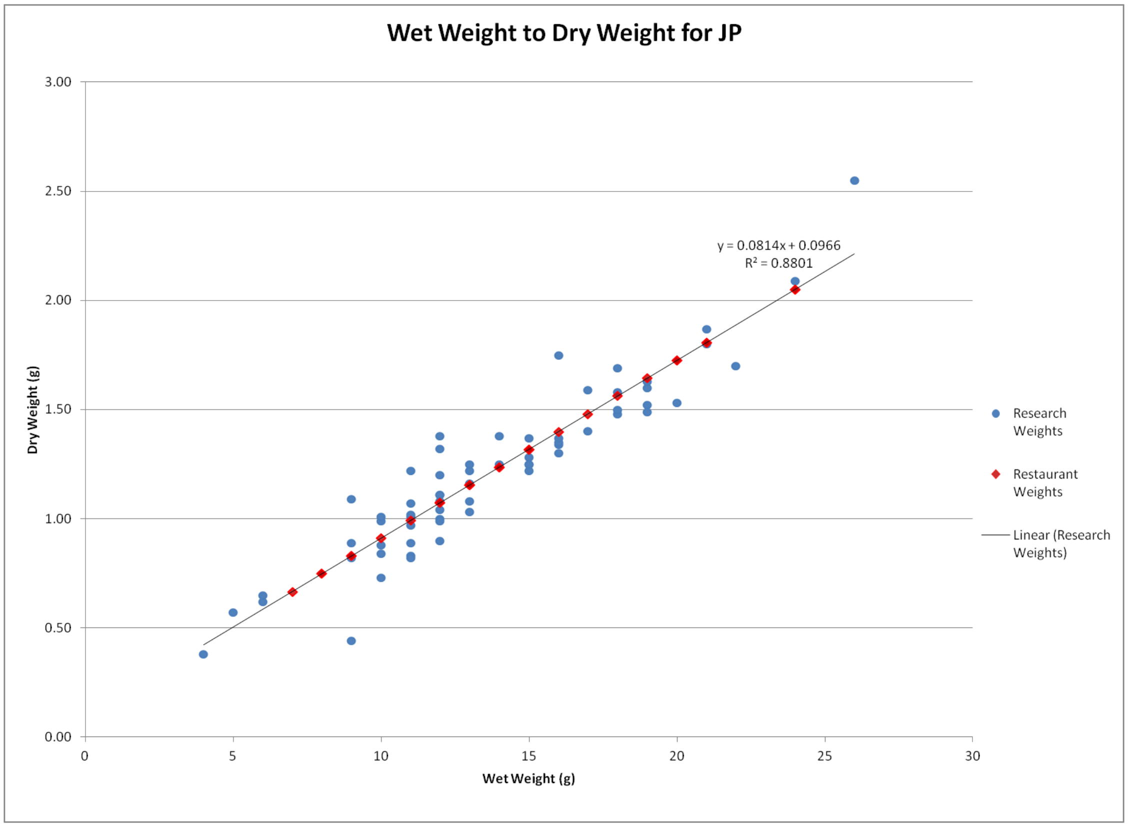


**Figure 32: Wet to Dry mass for JP. Field scale was used for wet weights and lab scale was used for dry. Restaurant weights were predicted based on wet field scale weights to dry lab scale weights in Excel.**

The r value for orange peppers (OP) was 0.91 with a corresponding $R^2$ value of 0.83. The total wet weight was 2658.5 g, of which 127 g was weighed by the restaurant. The total dry weight was 290.17 g, of which 17.16 g was predicted through Excel. (Fig. 33)

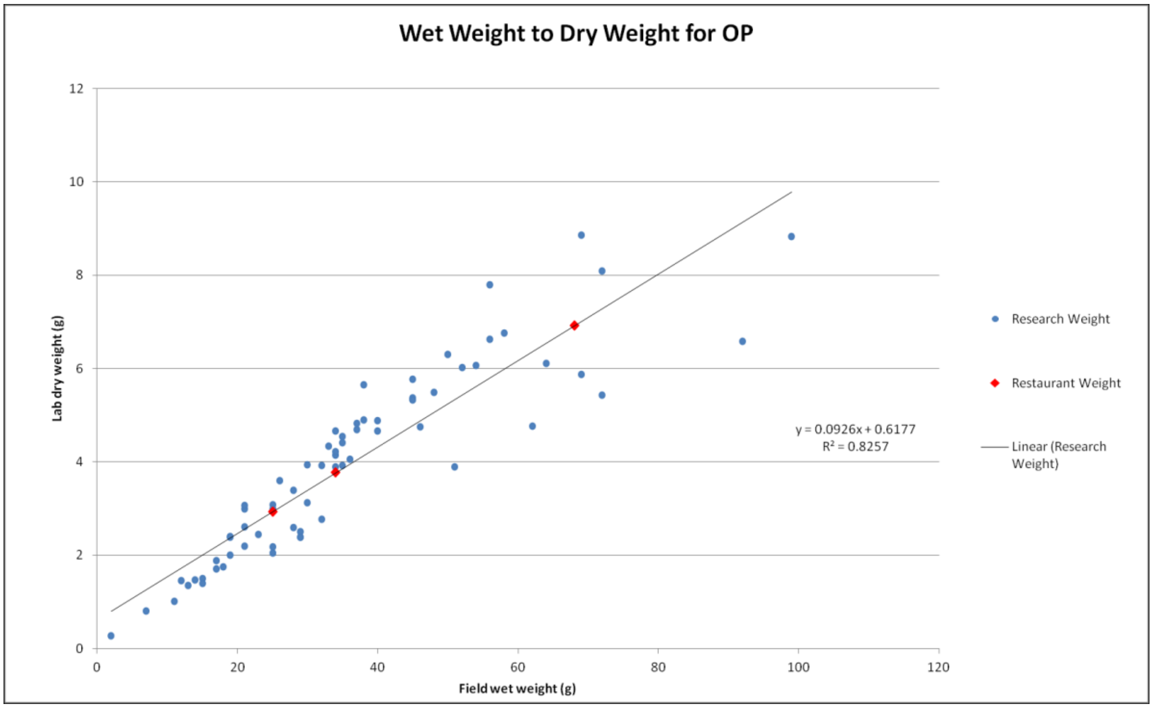


**Figure 33: Wet to Dry mass for OP. Field scale was used for wet weights and lab scale was used for dry. Restaurant weights were predicted based on wet field scale weights to dry lab scale weights in Excel.**

The r value for Roma tomatoes (ROMA) was 0.94 with a corresponding $R^2$ value of 0.88. The total wet weight was 2449.31 g, of which 959 g was weighed by the restaurant. The total dry weight was 212.61 g, of which 79.32 g was predicted through Excel. (Fig. 34) Roma weights can vary considerably, with the mean ranging between 62 g and 149 g (SELFNutrition Data; “Roma Tomato”). The lowest weights shown in Fig. 17 correspond to unripe, green tomatoes that were harvested along with above-ground biomass at the end of the growing season. The greatest weights were harvested by the restaurant at peak harvest time, whereas the fruits harvested by the researcher were early in, and at the end of, the growing season.

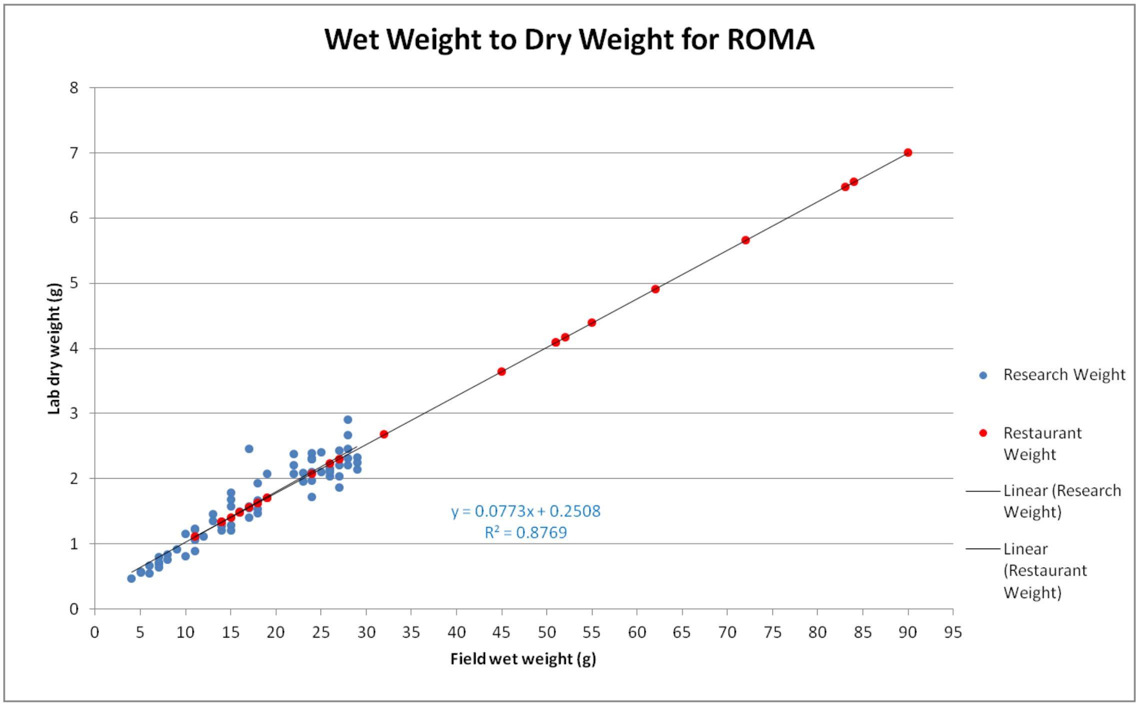


**Figure 34: Wet to Dry mass for ROMA. Field scale was used for wet weights and lab scale was used for dry. Restaurant weights were predicted based on wet field scale weights to dry lab scale weights in Excel.**

The r value for yellow peppers (YP) was 0.95. The total wet weight was 2019.22 g, of which 553 g was weighed by the restaurant. The total dry weight was 190.12 g, of which 51.62 g was predicted through Excel. (Fig. 35)

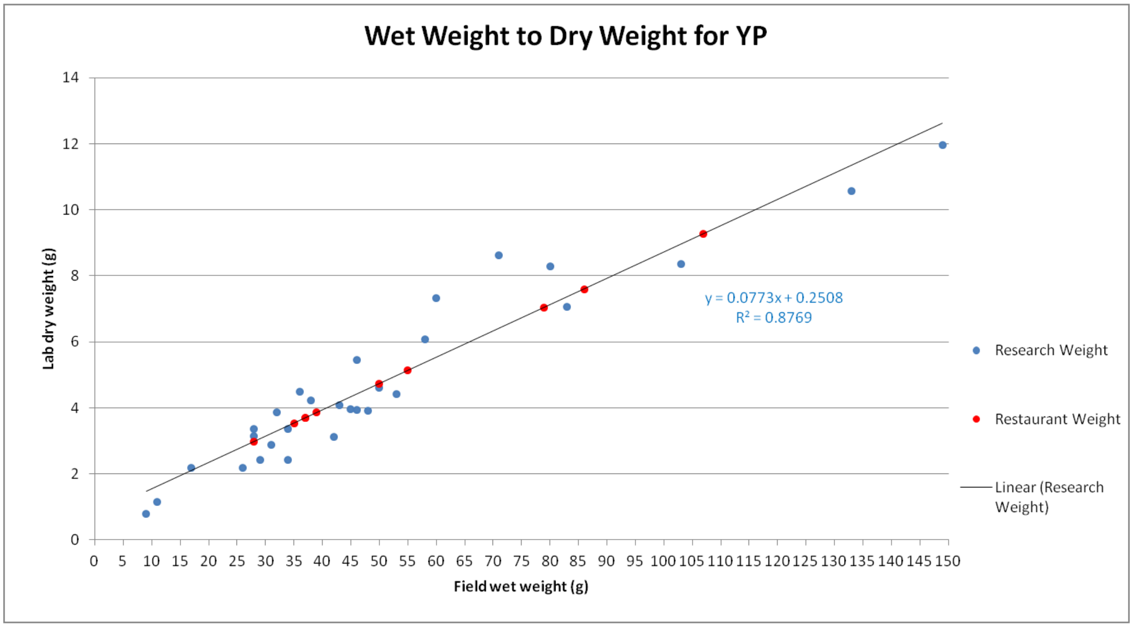


**Figure 35: Wet to Dry mass for YP. Field scale was used for wet weights and lab scale was used for dry. Restaurant weights were predicted based on wet field scale weights to dry lab scale weights in Excel.**

The r value for Siberian tomatoes (SIBER) was 0.99. The total wet weight was 467.12 g, of which 197 g was weighed by the restaurant. The total dry weight was 37.27 g, of which 15.96 g was predicted through Excel. (Fig. 36). SIBER is another indeterminate tomato variety that exhibits a vine-like growth pattern and requires ample room and staking. It was also placed in a small container (10” diameter, 9.5” depth), which inhibited growth and yield.

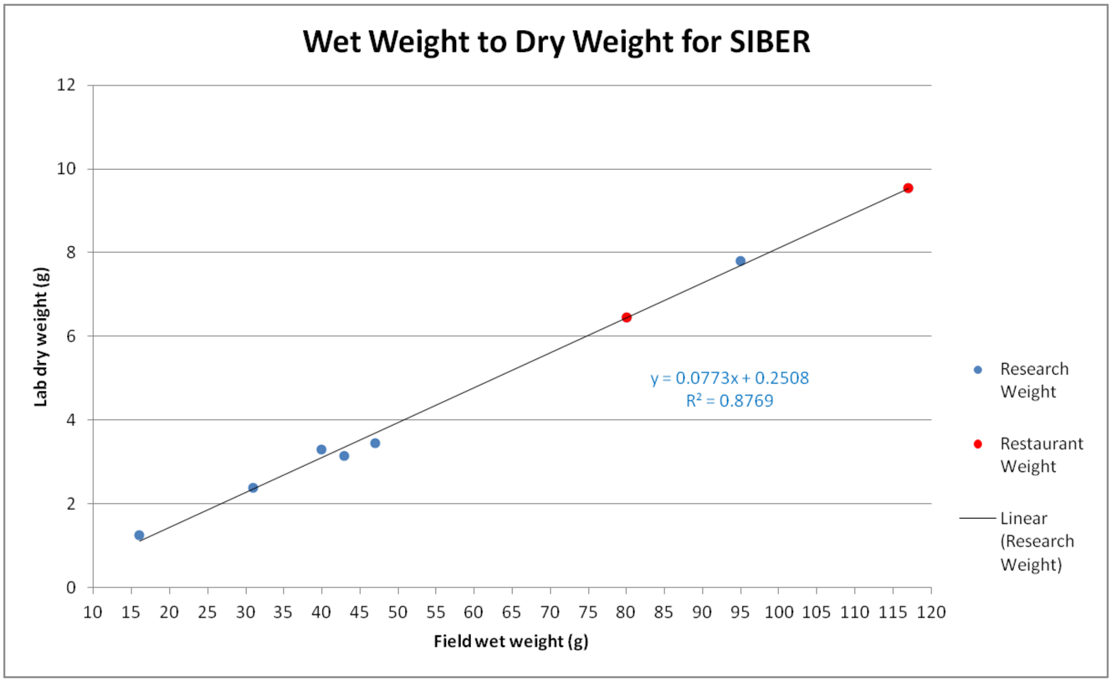


**Figure 36: Wet to Dry mass for SIBER. Field scale was used for wet weights and lab scale was used for dry. Restaurant weights were predicted based on wet field scale weights to dry lab scale weights in Excel.**

SS tomatoes had extreme variability in their wet:dry ratios due to problems with blossom rot in the RTG for this variety. Due to that, the wet weights were not a good predictor for the dry weights. Therefore, regression was run using the BB data, resulting in a total dry weight of 90.46 g, of which 53.09 was predicted through Excel. The total wet weight was 1902.19 g, of which 1045 g were weighed by the restaurant.

Only one rosemary plant was grown in the research garden and the total wet weight of the wet rosemary was 221.44 g, of which the chef harvested 36 g and used fresh. The remainder was dried by the researcher at the end of the season and the resultant dry weight was estimated by taking the average percentage of dehydration of the research mass and multiplying it by the 36 g the chef harvested. The total dry weight of the rosemary plant was therefore calculated to be 66.13 g, of which 10.96 g was estimated.

Overall, total biomass production in the 34 $ft^2$ of vegetated rooftop was 37.1 Kg of wet biomass and 5.04 Kg of dry biomass. This was comprised of the following values: wet biomass – researcher (32.4 Kg), restaurant (4.7 Kg); dry biomass – researcher (4.58 Kg), restaurant (0.41, predicted values). Of the wet biomass amount, 17.67 Kg was actual produce, with the remainder being plant matter . The correlation between wet and dry mass was high, with r values of 0.82 for Researcher and 0.90 for Restaurant. The total amount of $CO_2$ removed equates to 7.39 Kg for the total vegetated footprint, based on a generic photosynthesis equation:

$$CO_2 + H_2O + h\nu \rightarrow (CH_2O) + O_2 \tag{5}$$

# Chapter 5 Discussion

### 5.1.1. Storm Water Management

As discussed, CSOs can introduce pathogens, pollutants and floatable solids into receiving waters and therefore are of great concern to many cities around the world. By reducing storm water flowing into CSSs, RTGs help to minimize the impact of heavy storms on a municipality. The research RTG showed an absorbency rate of 96%, within the ranges shown by Spolek. (Spolek, 2008) Delay was not measured empirically on the RTG, but delays were noticed during watering as the outflow would at times continue to drip after all watering was completed. It is estimated to have taken approximately 30 minutes to water the RTG each time, thus a delay of approximately 30 minutes is reasonable.

Furthermore, while the volume of rain that fell in the RCs was a small value (only 55.57 gallons overall), this was only over the 13 $ft^2$ area that was covered by the RCs. Looking at the 238 $ft^2$ footprint of the total RTG shows that approximately 143 gallons of rain fell and with an absorbency rate of 96% established, 137 gallons were retained by the RTG overall. Additionally, when comparing RTG collected values with the published rain data from Pennsylvania State Climatologist, it can be seen that more rain fell than was measured. (Fig. 37) This was due, in part, to the restriction of days that researcher was able to access the RTG and therefore rain could not always be measured. If the square footage of the RC data was increased to 100 $ft^2$ and absorbency is plotted against the normal precipitation from the National Oceanic and Atmospheric Administration (NOAA) for Pittsburgh, PA for the period 1971-2000, it is clear that having an RTG of similar design as the research RTG would have a beneficial impact on managing storm water flow. (Fig. 38) When considering discharge versus precipitation on an annual period, and increasing the square footage that would be covered by an RTG, the amount retained at 1000 $ft^2$ shows an even greater beneficial impact. (Fig. 39)

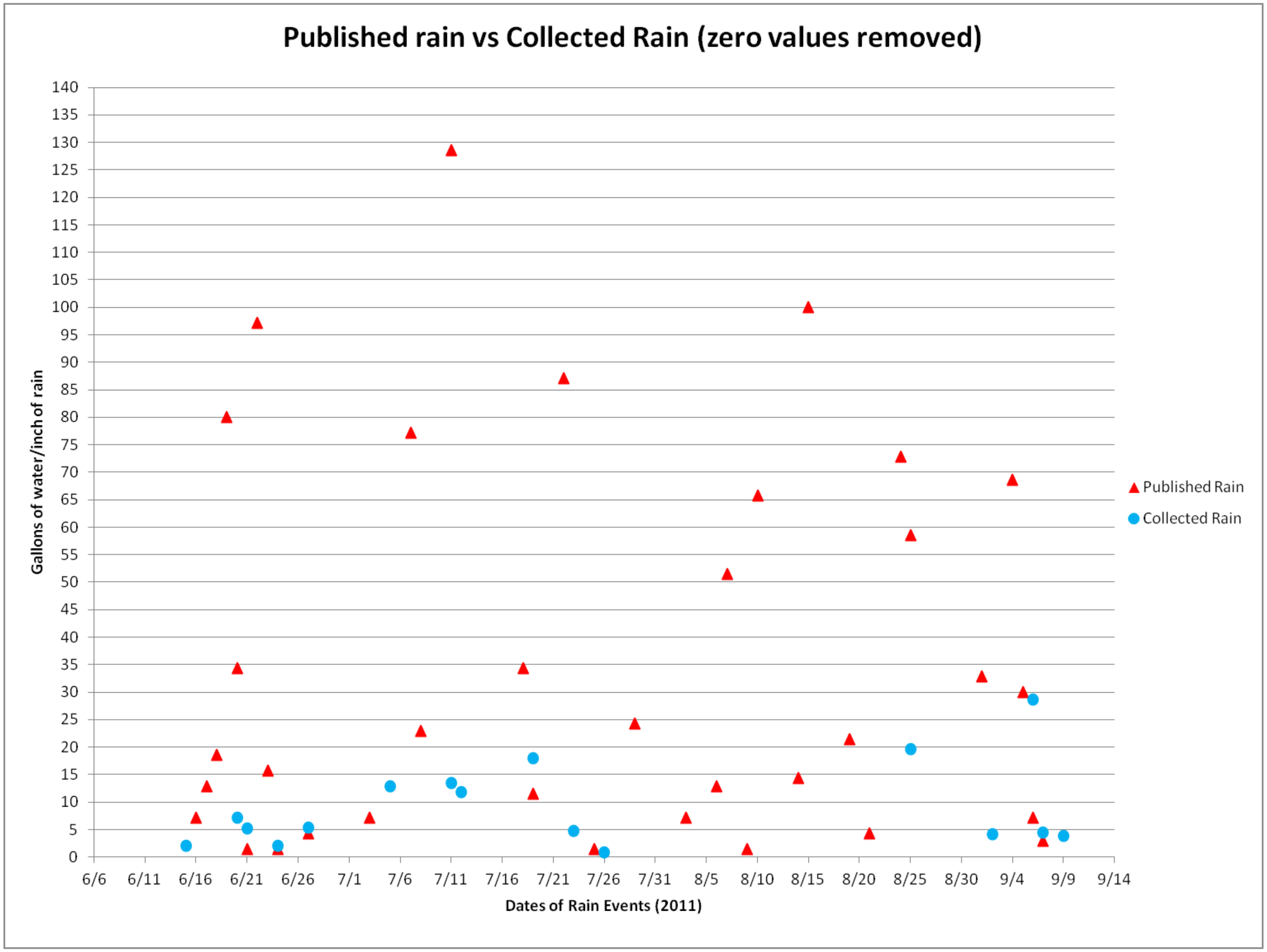


Figure 37: Comparison of published rain data and RTG collected rain data. Published rain data was obtained from Pennsylvania State Climatologist. http://climate.met.psu.edu/www_prod/

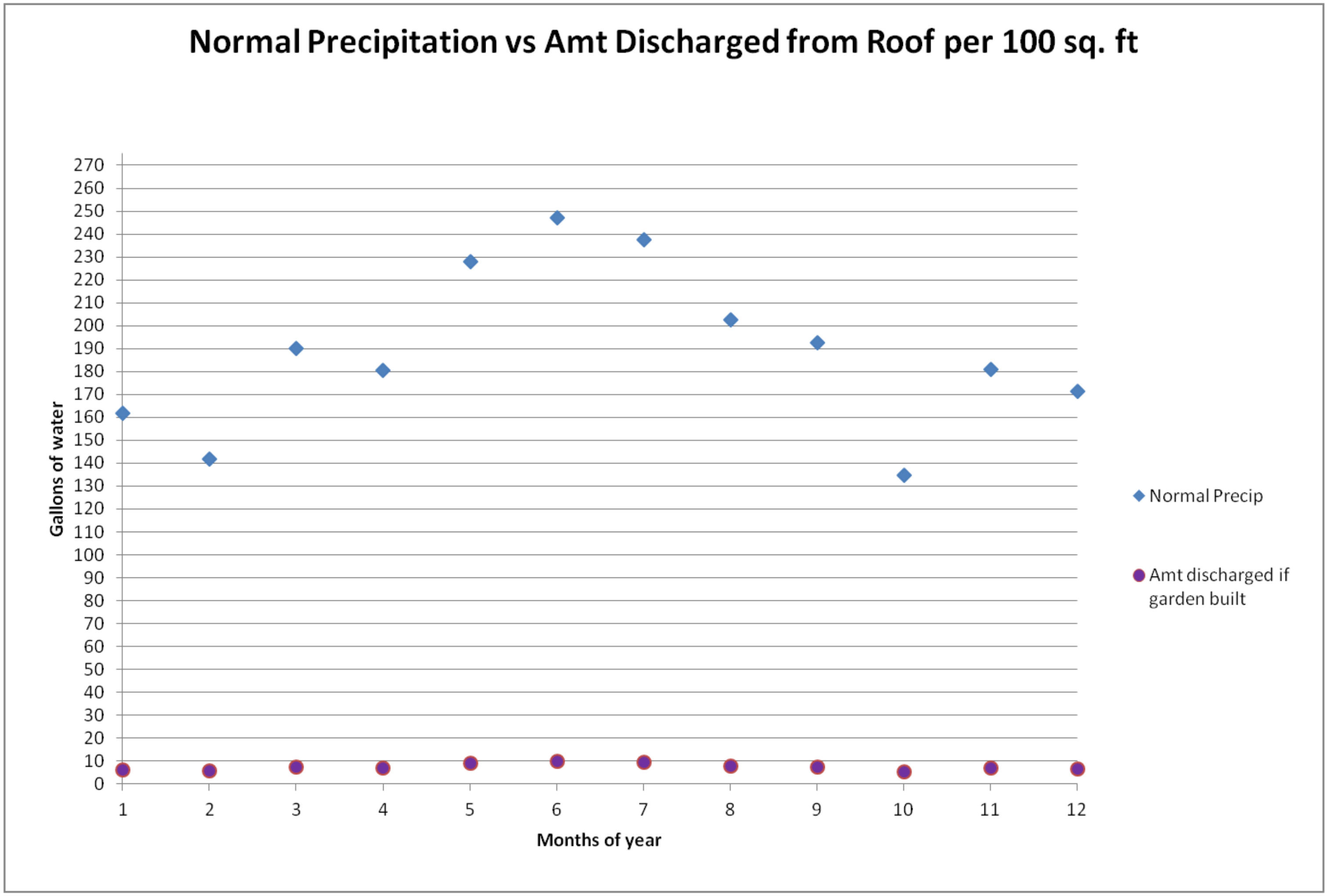


**Figure 38: Monthly precipitation levels for Pittsburgh, PA and volume that would be absorbed per 100 ft$^2$ of vegetated roof. The peak benefit would be realized during peak rainfall, months 3-9, with minimal absorption being realized in the winter months. Precipitation data obtained from NOAA. http://www.ncdc.noaa.gov/oa/ncdc.htm**

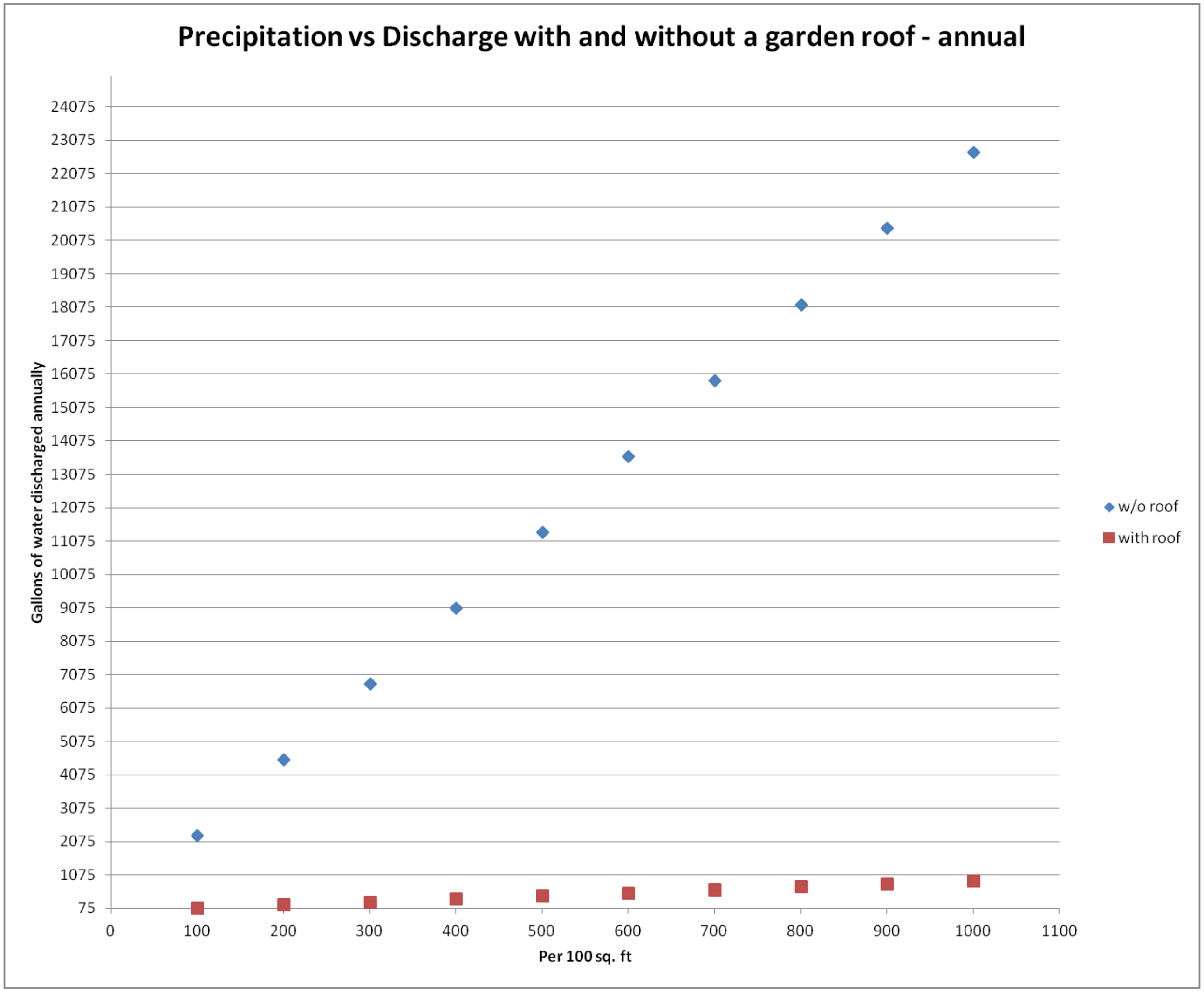


**Figure 39: Data based on annual published precipitation amounts for rainfall, with 96% absorption rate applied for roof retention.** **http://www.ncdc.noaa.gov/oa/ncdc.htm**

It was noticed during supplemental watering that if the soil mix was completely dry, the water was not easily absorbed but instead exited the RCs almost immediately. If the soil mix contained some level of moisture prior to a rain event, then the precipitation was more completely absorbed. This is borne out by both soil saturation studies as the grab sample experiment had a volumetric water content of 0.44 whereas the homogenized sample's value was 0.79 but both had soil porosity calculated at 0.86. Volumetric water content is a measurement of the volume of liquid per mass of dry soil. Thus a value of 0.44 indicates that just over half (51%) of the pore space is filled with water and 0.79 indicates that almost 93% of the pore space is filled with water. Since these values are calculated after saturating the soil sample, the values show that the grab sample already had some level of moisture in it, similar to what would have been seen on the RTG most days. Furthermore, when the homogenized sample was used in the lab, the sample had to be stirred vigorously and time had to be given for the soil mix to absorb the water, similar to the method that had to be used prior to placing the soil mix into the planting boxes. Soil porosity is the maximum volumetric water content that a soil can hold. Thus, the 0.86 porosity value indicates that at maximum saturation, the soil can hold 87% of its volume in water. This will not only help to reduce and delay the flow, but helps to retain moisture should access to the RTG be restricted. There were several occasions where the RTG did not receive any input, either from rain or supplemental watering, for as much as 6 days. (Fig. 24) While the plants were quite wilted, they not only survived but continued to produce. It must be noted, however, that the yield of the RTG was not as great as needed and the lack of consistent irrigation may have played a factor in the limited growth. Therefore, a mix such as that used on the RTG has been shown to be ideal in terms of maximum water retention, while providing a lightweight, easily amendable medium at low cost, but one that was nutritionally deficient. Supplemental chemical fertilization was therefore required and it is unknown how much of this fertilizer may have been absorbed by the plants versus discharged into outflow.

### 5.1.2. Biomass

Placing an RTG on an otherwise bare surface follows the progression laid out by Shi et al. A non-vegetated roof contains no soil or biomass and therefore has zero capacity to sequester $CO_2$. An RTG becomes similar to crop land as it is capable of producing food, while providing benefits similar to extensive roofs in terms of storm water management and aesthetic value. As Davison notes, 38% of all $CO_2$ emissions comes from non-point sources, with 24% of that coming from transport emissions. With urban centers becoming increasingly populated, RTGs in an urban environment can help to mitigate the impact of those emissions.

When comparing the $CO_2$ sequestration potential of the RTG to published research, it should be noted that most of the published data centers on carbon stock. Data presented in this thesis is based on the photosynthesis equation and centers on $CO_2$. By using the moles to grams ratio, 7.39 Kg of $CO_2$ was used, and therefore sequestered, by the RTG. As was the case with the storm water management values, this appears to be a minimal amount but it must be remembered that only 34 $ft^2$ of the roof was vegetated. If the amount of roof covered increased, so too would the amount of $CO_2$ removed, similarly to what was seen in the storm water management graphs**.** For instance, while 34 $ft^2$ of vegetation sequestered 7.39 Kg, 100 $ft^2$ of vegetation can sequester 22 Kg and 1000 $ft^2$ can sequester 220 Kg, based on these results. (Fig. 40) Furthermore, Figure 41 shows that if 10,000 houses had a 100 $ft^2$ of vegetated RTG, $2.0 \times 10^5$ Kg of $CO_2$ would be sequestered.

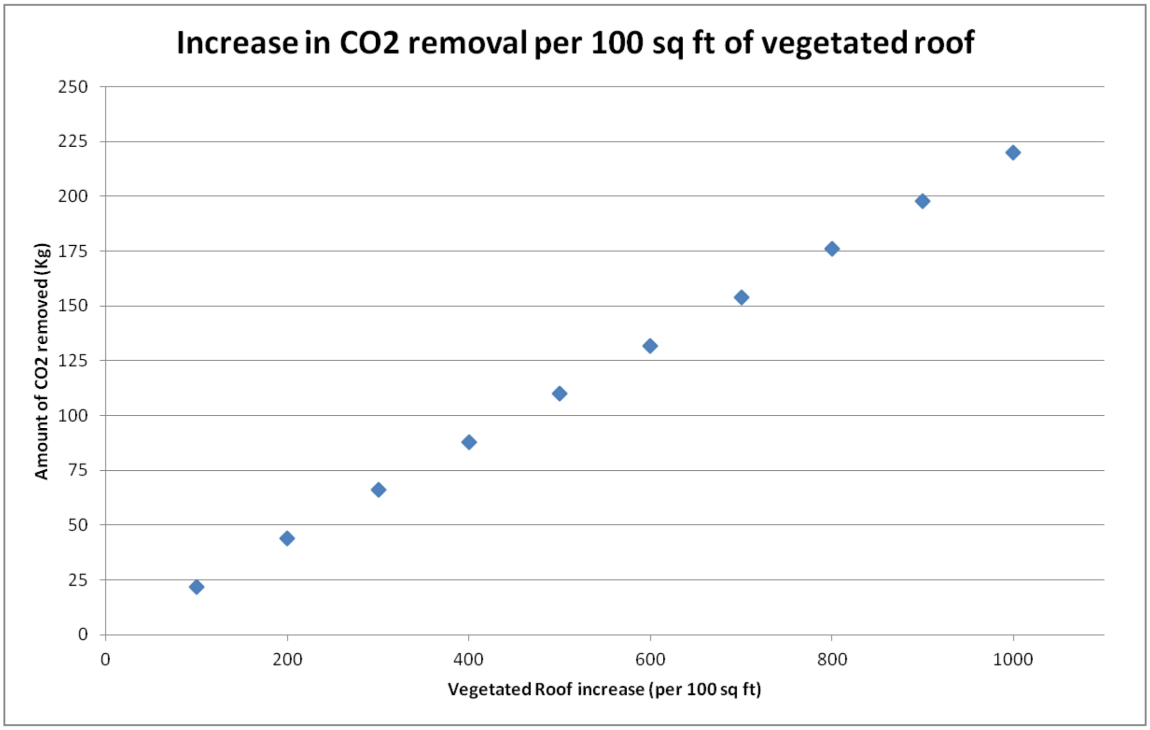


**Figure 40: Illustrates the increase in potential $CO_2$ sequestration by an RTG as square footage increases.**

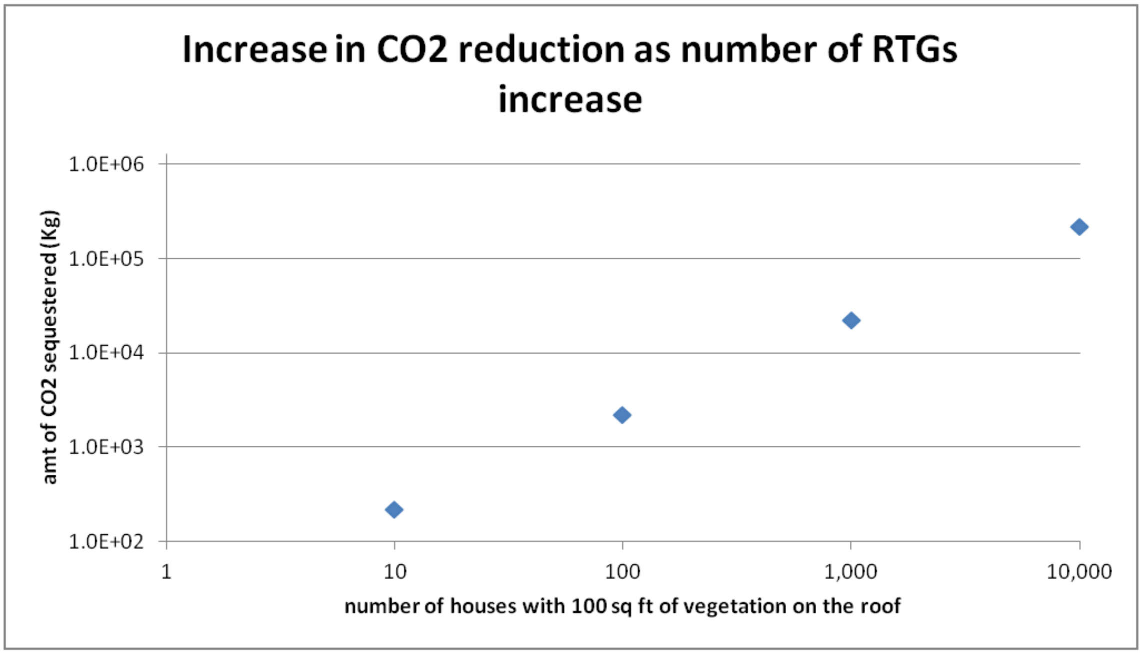


**Figure 41: Illustrates the increase in potential $CO_2$ sequestration as number of houses with an RTG increases.**

### 5.1.3. Secondary considerations

### 5.1.4. Yield

The RTG was originally intended both to serve as a research roof and for production of boutique vegetables for the restaurant. The volume of vegetables that the restaurant used in an average week was provided by the chef and is shown in Table 4.

**Table 4: Weekly average consumption of fresh produce purchased by eating establishment**

| Type of Produce used by Restaurant | Average Weekly Use |
|---|---|
| Mixed greens (baby spinach, arugula, red oak lettuce, frisé) | 6 lbs |
| Zucchini | 5 lbs |
| Yellow squash | 5 lbs |
| Iceberg lettuce | 8 heads |
| Romaine lettuce | 24 heads |
| Red bell peppers | 15 lbs |
| Green bell peppers | 5# |
| Whole carrots | 10# |
| Green beans | 20# |
| Celery | 10# |
| Onion | 20# |
| Spinach | 15# |
| Tomatoes | 30# |
| Strawberries | 5# |

Not all the varieties listed could be grown for this experiment, due to unavailability, although all varieties could hypothetically be grown on an RTG. Therefore total pounds were used for comparison. The restaurant used an average of 140 pounds of vegetables in a given week, excluding lettuces, and the RTG produced on average only 3 pounds of vegetables per week. However, this was grown in only 34 $ft^2$ of growing space and contained different varieties than what the restaurant normally used. In order to grow the amount of produce needed on average, a larger area would need to be planted. The average American family consumes 3.9 pounds of fresh vegetables weekly and with an average weekly yield of 3 pounds, it has been demonstrated that a 238 $ft^2$ RTG can produce enough to feed the average family during the growing season ("Profiling Food Consumption in America" 2000). Furthermore, the goal for the restaurant was to grow specialty vegetables that they couldn't obtain through their vendors. The RTG accomplished this, albeit on a limited scale, by producing heirloom tomatoes in 4 varieties in addition to orange and yellow bell peppers – all of which are generally higher cost items. In order to achieve greatest return on investment, a commercial establishment should strive to grow hard-to-find or high-priced items. For a residential building, greatest benefit would be achieved by growing commonly consumed vegetables.

Some of the plants had a very low yield, as was the case with BCW (n=4). This heirloom tomato is indeterminate, meaning that has a vine-like growth pattern and requires ample room and staking. The plant was placed in a smaller pot (~11” diameter and 9.5” in height), which inhibited its growth and yield. Similar results were seen with the Siberian tomato and also the zucchini, which is another plant that requires ample growth room. Other varieties, while prolific, showed a lower average weight than the published average weight. For instance, the mean weight of Roma tomatoes ranges between 62 and 149 g, whereas the majority of the RTG Romas were well below that weight. However, this can be attributed to several factors, such as lack of growing space for the individual plants and inconsistent irrigation, which also contributed to blossom rot on the SS varieties. A higher yield could be achieved by using larger, self-watering containers.

Cost was a factor throughout the project, but this was appropriate as the RTG was intended to be economically manageable for the general public. The cost to build the garden for the soil mix, fertilizer, plants and miscellaneous materials came to approximately $200, an amount that could prove to be easily affordable by most, when compared to the cost of purchasing the same vegetables. If a permanent structure was built, the initial cost may be higher. However, subsequent years would cost less as only plants, and possibly fertilizer, would need to be purchased . Since an RTG can help reduce storm water runoff and can help to provide food for a family, by keeping cost low it is more likely that an RTG could become an economically viable option for many residences and as such, has a greater chance of high levels of participation. In order for an RTG to be productive enough for an eating establishment, school, or small business, a larger investment for vegetation, more permanent planting structures and better soil would be required.

### 5.1.5. Box Design

As discussed previously, the RCs had two basic designs: one that had two bags and one that had one bag. In both cases, the bag was sealed around the cardboard box to ensure that only rain that fell in the soil and drained out would be measured. Planters without RCs were built in various manners to determine the viability of using different designs outdoors. Some of these boxes were only wrapped on the outside, some only had minimal plastic on the inside and some were milk crates lined in plastic. The RCs held up remarkably well, with little deterioration of the box structure or drainage board noticed. (Fig. 42).

**Figure 42: Examples of different types of containers tested. Upper left - has a partial bag on the inside of the box. Upper right – constructed of a milk crate with a bag inside, and also a bag taped around. Bottom: RC early in the season (left) and at end of season (right). Exterior bag has been removed in top pictures to show the structural stability of the planters.**

For the most part, the boxes held up well as long as they were not moved, jostled or knocked over – all of which occurred at various times and to several boxes in the RTG. After approximately one month, the cardboard had become saturated to its maximum extent such that any movement resulted in destruction of the box. Several boxes had to be rebuilt throughout the project due to being knocked over by the researcher. Surprisingly, none of the built planter boxes were knocked over by the strong winds Pittsburgh experienced in the summer of 2011, although the plastic milk crates and plastic pots were. Additionally, some of the boxes were the incorrect size to support the mature plant and several of the plants became root-bound. (Fig. 43) It is possible that this also contributed to the low overall yield.

**Figure 43: Example of root-bound plant in one of the planter boxes.**

### 5.1.6. Biodiversity

Biodiversity was not a focus of this research, but it could not help but be noticed. The control roof remained bare, with only a rain gauge to collect precipitation and there were no insects noticed on it. On the RTG, however, several species of insects were noted, with most residing directly on the plants and a few on the planter boxes. (Figs. 44-46, species noted where able to be identified)

Figure 44: Unidentified moth on side of floor support beam. Photo taken 7/12/2011.

Figure 45: Common grasshopper sitting on banana pepper plant. Photo taken on 8/28/2011.

**Figure 46: Stink bug nymph on zucchini. Photo taken 7/12/2011.**

**Figure 47: Adult mayfly perched on plastic covering planting supplies on RTG. Photo taken 6/15/2011.**

One interesting insect that was noticed is the mayfly adult (Fig. 47). Adult mayflies are short-lived, with a life cycle of only a day or so and they mate near a running water source. The Monongahela River is approximately 0.2 miles from the restaurant but two adults were spotted on one of the planter boxes. Since no insects were observed on the non-vegetated control roof and since most of the insects were observed on the plants, it can be assumed that the RTG provided a suitable habitat. This is in line with other published research that shows that extensive roofs increase biodiversity.

### 5.1.7. Complications encountered during project

Several complications arose during the research project that bear discussion as these difficulties may also be encountered during future research efforts. As mentioned earlier, the research roof was located on the top of a local Pittsburgh restaurant. The owner also had an office and conference room in the building, which were used to access the roof (Fig. 5) As such, access to the roof was restricted to only those times that the secretary was available to provide entry. Since the restaurant owner also had other business concerns, the secretary was often out of the building for external meetings, and worked Monday through Friday from 7 am to 4 pm. If meetings were being held on site in the conference room, access to the RTG was also denied. Restricted access made it difficult to maintain a regular supplemental watering schedule, which likely played a part in reduced crop yield.

Water supply was also an issue as water from the restaurant was used to provide supplemental watering. The RTG was approximately 30’ above ground level (Fig. 5) and no hose was available due to limited funds. Therefore, water was initially manually carried to the roof in 5 gallon buckets. The RTG required approximately 40 gallons on average, resulting in at least 8 trips from ground to roof for each supplemental watering session. The chef was unable to water in this fashion as his presence was obviously needed in the restaurant kitchen, further increasing the inconsistent irrigation and reducing crop yield.

For these two reasons, egress and a readily available water source to an RTG is essential to the success of any future endeavors and should be considered at least as important as structural stability when determining whether a given roof is appropriate for an RTG. Design adjustments could be made for the water supply, such as collecting rainwater in rain barrels or using self-watering containers for the crops, but restricted access to the roof is difficult to design around.

# Chapter 6 Conclusion

It has been demonstrated by this research that RTGs have a limited capacity to help sequester $CO_2$, but even limited capacity for $CO_2$ uptake is better than no capacity, which is what a bare roof exhibits. Buildings and homes would need to be assessed by an architect or structural engineer to determine structural stability. The roof must have egress for materials and workers such that garden maintenance and harvesting can be performed. A supplemental water supply must be available. Alternatively, if the building were determined to have the appropriate structural stability, a rain barrel or self-contained system could be utilized. Municipal codes must be checked for any historical restrictions and egress requirements under the Americans with Disabilities Act. For these reasons, an RTG may not be appropriate for all buildings. The RTG was demonstrated to absorb up to 96% of rainfall, which is in line with published research rates by Spolek and Simmons. By retaining a large part of the volume of water in any given rain event, RTGs can help mitigate CSO events in cities that have CSSs.

Further research should be conducted to verify these results, in addition to correcting any experimental flaws inherent in the design. Cardboard boxes provide an economical but seasonal alternative to planters, but do not remain structurally stable after several months. Thus, an RTG built in this fashion would not provide green roof benefits for part of the year. For yearly benefits to be realized, the RTG should be designed with permanence in mind and built of weather-resistant materials. Different types of planters should be tested to determine the best design to provide optimal retention of storm water runoff. Additionally, while the mix used had a high absorbency rate, it was nutritionally deficient and required chemical fertilization to keep it productive. If another roof becomes available for this research to continue, different soil mixes should be used to determine the optimum mix of soil that would provide a lightweight, nutrient-dense and highly absorbent medium.

Another area of interest centers on the adaptability of this model for different environments. Pittsburgh has a temperate summer climate with an extended growing season and is well suited to all the crops used. However, an arid environment would require frequent irrigation, increasing stress on drought-prone areas, whereas a wetter environment might benefit from crops that require high levels of moisture, such as tomatoes. Accordingly, research into crop varieties best suited to a particular environment would be beneficial.

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