VEGETABLE PRODUCTION USING GREEN ROOF TECHNOLOGY AND THE POTENTIAL IMPACTS ON THE BENEFITS PROVIDED BY CONVENTIONAL GREEN ROOFS

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ABSTRACT

VEGETABLE PRODUCTION USING GREEN ROOF TECHNOLOGY AND THE POTENTIAL IMPACTs ON THE BENEFITS PROVIDED BY CONVENTIONAL GREEN ROOFS

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Modern green roofs, which originated in Germany in the late 1800's, reduce energy use, mitigate urban heat island effects and reduce stormwater release. In recent years more attention has been turned to two additional potential benefits of green roofs; carbon sequestration and vegetable production. Although some work has been done on extensive *Sedum spp.* roofs, little has been done on carbon sequestration of other green roof types and other ornamental landscapes. Little literature also exists on the use of green roofs in urban agriculture.

Urban agriculture has many benefits including increased economic and food security, job creation and community building, but is also faced with many challenges. The largest of which is land availability and competition with other forms of land development. The use of green roofs could eliminate this form of competition at some locations and help to alleviate other concerns surrounding urban agriculture such as health hazards associated with heavy metal contamination of food. It does however raise two other major concerns; how the added weight of the green roof and the weight load restrictions of most flat roofs will affect the scale at which it can be implemented and how higher nutrient requirements of vegetable and herb plants compared to most other green roof plants will affect runoff water quality. Four studies were designed to examine food production on extensive green roofs and the ability of extensive green roofs and other ground level ornamental landscapes to sequester carbon.

Vegetable species selected for study were tomatoes (*Lycopersicon esculentum*), green beans (*Phaseolus vulgaris*), cucumbers (*Cucumis sativus*), peppers (*Capsicum annuum*), basil (*Ocimum basilicum)* and chives (*Allium schoenoprasum*). These were tested for their productivity on an extensive green roof, extensive green roof platforms and in ground. All plants survived and produced biomass at all three locations for three growing seasons. Use of three mulching strategies (no mulch, pine bark mulch, and a living *Sedum* mulch) and three fertilization regimens (25, 50, and 100 g/m^2 of a 14-14-14 N-P-K slow release fertilizer applied twice during each growing season) were examined and the use of pine bark mulch and higher fertilizer application rates improved crop performance. Further research on other mulches and fertilizers is recommended to optimize vegetable and herb production. To examine effects of vegetable and herb production on the stormwater benefits provided by green roofs, stormwater runoff quantity and water quality were compared with more traditional extensive green roofs planted with a sedum mix and a native prairie mix. The prairie mix retained the most runoff and the vegetable and herb mix the least because of differences in plant density and morphology. Examination of runoff nitrate and phosphorus concentrations had mixed results with no differences among treatments for nitrate and higher phosphorus concentrations in the first 125 mL of runoff from the vegetable and herb green roofs. Further research into nutrient runoff is recommended. Finally the ability of nine in ground and four extensive green roof landscapes, including vegetable and herb gardens, to sequester carbon were compared. The in ground landscape systems sequestered more carbon than the corresponding green roof landscape systems. Most carbon was sequestered by landscape systems containing plants with large amounts of woody structures or high plant volumes, but more research on the effect of management practices is recommended.

The following is dedicated to Ruth, who first helped me to discover my passion for green roofs and my family for their continued support throughout the course of my education.

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Introduction

Although the term “green” has come to be associated with many environmentally friendly technologies, corporations, and policies, “green roof” refers specifically to a roofing technology that enables the growth of vegetation on rooftops. The environmental benefits attributed to this type of roofing include reduced air and noise pollution, increased habitat and biodiversity, increased roof lifespan, stormwater retention, energy savings and mitigation of the urban heat island effect (Alexandri and Jones, 2008; Barrio, 1998; Carter and Jackson, 2007; Getter and Rowe, 2006; Getter et al., 2007; Loder and Peck, 2004; Rowe, 2011; Saiz et al., 2006; VanWoert et al., 2005a; Wong et al., 2003). Green roofs have also been shown to provide a wide variety of health benefits (Ulrich, 1981, 1984) and when open to the public can provide recreation opportunities.

Green roofs are typically constructed of several layered materials that facilitate vegetative growth. The specific makeup of these layers will depend on building load capacity, purpose of the project (Getter and Rowe, 2006) and manufacturer. These layers include a root barrier to protect the underlying structure from root penetration, a drainage layer to facilitate water movement off the roof, a filter fabric to minimize the loss of substrate and subsequent clogging of the drainage layer, an optional water retention fabric (Getter and Rowe, 2006), growing substrate, and the vegetation itself. Substrate composition varies, but the primary component is a light-weight, mineral based material, such as heat expanded slate (Getter and Rowe, 2006). Substrate depth and the vegetation used vary between roofs. Extensive green roofs, those with less than 15 cm of substrate, are low maintenance, usually rely on natural precipitation (Durhman et al., 2006), and are typically planted with succulents, grasses, herbs, or other ground cover species (Getter and Rowe, 2006). Intensive green roofs, those with more than 15 cm of substrate, require greater structural support and often more maintenance than extensive roofs, but can support a greater diversity of plants.

The History of Green Roofs

The first modern green roofs were constructed in Germany in the 1880's during a period of rapid urbanization (Kohler and Keely, 2005). A highly flammable, inexpensive tar was commonly used on roofs at the time and in an effort to reduce this fire hazard, a roofer, H. Koch, began covering such roofs with sand and gravel (Kohler and Keeley, 2005). These sanded roofs were gradually colonized by local plant life and 50 of these original roofs were still intact and waterproof in the 1980's (Kohler and Keeley, 2005). Roof gardens on city department stores in the early 1900's (Firth and Gedge, 2005; Mikami, 2005) and the use of sod roofs for airfield hanger camouflage during World War II (Firth and Gedge, 2005) are some examples of early, intentional, modern green roofs. The first large-scale green roof project was constructed at the Free University of Berlin by Reinhard Bornkamm after the rediscovery of Koch's roofs in the 1960's (Kohler and Keeley, 2005). Since then, interest in green roofs has increased in Europe (Kohler and Keeley, 2005), although significant interest in the United States did not arise until much later (Cheney, 2005; Lipton, 2005).

The current growth of the green roof industry in the United States (Getter and Rowe, 2006) has been enhanced through a number of incentive programs (Cheney, 2005; City of Portland, 2009b; City of Chicago, 2005a, 2006; Kula, 2005; Lipton, 2005). Cities such as Portland, Oregon, and Chicago, Illinois, have been applauded for their inclusion of green roofs in stormwater management (Lipton, 2005), offering incentives for the use of green roofs in building plans (City of Chicago, 2005b, City of Portland, 2009a), and making financial assistance for the installation of green roofs available (City of Portland, 2009b; City of Chicago, 2005a, 2006). The Leadership in Energy and Environmental Design (LEED) program provides further incentive to builders and corporations. LEED was developed by the US Green Building Council as a tool to promote and measure green building design, construction, operation, and maintenance (USGBC, 2011). It employs a number of rating systems that award points (100 possible) in the categories of sustainable sites, water efficiency, energy and atmosphere, materials and resources, and indoor environmental quality with additional bonus points (10 possible) in the categories of innovation in design and regional priority. Up to 15 points toward certification can be earned by incorporating a green roof in the building design, with the possible addition of points for innovative design (Kula, 2005).

Plant Selection for Green Roofs

There are many criteria for selecting plants for installation on a green roof, some of which are interconnected. It is important to consider the hardiness of potential plant species, because rooftop plants are exposed to harsh temperature and irradiance extremes, wind, and may rely solely on precipitation for water (Getter and Rowe, 2006; Getter et al., 2007). Succulents, such as sedums, are often used in extensive green roofs because of their ability to survive such conditions. Deeper substrate and more intensive maintenance can enable the use of less drought tolerant species through greater water retention (VanWoert et al., 2005a) and irrigation. Careful selection of plant species can ensure survival of individual plants and self-sustaining populations (Getter and Rowe, 2006), which influence the extent of benefits received from the green roof (Getter and Rowe, 2006; VanWoert et al., 2005b; Wong et al., 2003).

Plant selection may also be dictated by the purpose of the roof project and the desired roof appearance. If a more natural habitat is the goal of the project, native species may be preferred. Irrigation is, however, usually necessary not only for establishment of native taxa on the roof (Monterusso et al., 2005), but for long term survival of individual plants and the plant community as a whole (Durham et al., 2006; Monterusso et al., 2005), resulting in greater maintenance needs. Although the survival of native plants on a green roof will depend on local climatic conditions, drought tolerance of selected species, depth of substrate, and management practices, there are many examples of native vegetation on green roofs (Arpels et al., 2005). In recent years, interest in the production of vegetables and herbs on green roofs has been increasing (Arpels et al., 2005; Loder and Peck, 2004; Whittinghill and Rowe, 2011).

Traditional Uses of Green Roofs

Energy savings and mitigation of the urban heat island (UHI) are two benefits of green roofs that make them particularly appealing in light of growing concerns about climate change and greenhouse gas (GHG) emissions. Stormwater retention is also particularly important in cities where it is difficult to manage the water flowing off impervious surfaces during a storm. Although other benefits of green roofs are also important, these have had an impact on current policies in the United States, such as stormwater utilities (Cater and Keeler, 2008, Lipton, 2005).

Green roofs have half the negative environmental impact of conventional roofs over the lifetime of the roof (Kosareo and Ries, 2007). Energy savings of an extensive green roof as compared with a conventional roof have been estimated between 1.2 and 8.5 % over the life of the roof (Saiz et al., 2006; Wong et al., 2003), and between 6 and 87 % reduction in cooling load during the summer depending on the building height and insulation, and distance of the floor from the roof (Santamouris et al., 2007).   Some of this reduction is due to insulation provided by the additional layers in a green roof, which reduce heat flux through the building roof (Barrio, 1998; Wong et al., 2007). This reduction in heat flux through the roof has also been found on inverted roofs, where the insulation is placed above the waterproofing membrane (Getter et al., 2011). Reductions in building energy use result in less environmental loading, fewer SO_X and NO_X emissions, and a smaller impact on human health (Kosareao and Ries, 2007).

To help building designers and owners better estimate the energy savings that could be accomplished through the use of a green roof, researchers have developed an energy calculator (Bass and Sailor, 2010; GBRL, 2011). The calculator estimates energy use for conventional, white reflective, and green roofs based on building information. Currently, the calculator is only calibrated for new construction, without irrigation (GBRL, 2011), but will soon include retrofitted roofs and estimates of stormwater retention and UHI mitigation (Bass and Sailor, 2010). This calculator could be a valuable tool for maximizing the energy savings of a building.

Secondary energy reduction can also be achieved through mitigation of the UHI effect. Green roofs have been shown to provide significant roof level temperature reductions (Wong et al., 2007), which are projected to extend to urban canyon microclimates (Alexandri and Jones, 2008).   When green walls are included in urban building designs, further air, surface, and non-vegetated surface temperature reductions are expected (Alexandri and Jones, 2008). These cooling effects result in urban temperatures more comfortable for human inhabitants, further reducing the need for indoor cooling (Alexandri and Jones, 2008). In some climates, it is projected that the need for summer cooling could be eliminated entirely (Alexandri and Jones, 2008).

Both direct and indirect energy savings of green roofs contribute to a reduction in carbon emissions produced during the generation of the electricity used to cool buildings in the summer. Assuming a 2% reduction in electricity and 9-11% reduction in natural gas consumption (Sailor, 2008), a generic building, and the US average CO_2 production for generating electricity and burning natural gas, one could expect annual savings of 2.3 to 2.6 kg CO_2 m^{-2}, and 0.24 to 0.97 kg CO_2 m^{-2} from electricity and natural gas, respectively (Rowe, 2011). If 1.1 km^2 of flat roofs (the flat roof area of the Michigan State University in East Lansing, MI, for example) were greened it is estimated that 3.64 million kg CO_2 emissions would be avoided each year (Rowe, 2011). This would greatly contribute to efforts to reduce anthropogenic CO_2 emissions, which were estimated to be 6,822 million mT CO_2 Eq for the United States in 2010 (USEPA, 2012).

Stormwater management is a third benefit of green roofs that plays a role in policy and construction decisions. The city of Portland, Oregon, for example, has incorporated the stormwater management provided by green roofs into their municipal stormwater management regulations (Lipton, 2005). Green roofs have been shown to retain between 52.4 and 100% of precipitation depending on slope, substrate depth, substrate moisture content, evapotranspiration rates, vegetation, and precipitation event size (Czerniel Berndtsson, 2010; Getter et al., 2007; Hathaway et al., 2008; Rowe, 2011; VanWoert et al., 2005a). Green roofs also provide a delay in peak runoff of at least 15 to 30 min, compared to gravel ballast roofs (Hathaway et al., 2008; VanWoert et al., 2005a). These reductions and delays in stormwater runoff can reduce loads to municipal stormwater systems, which are often overtaxed during precipitation events (Getter and Rowe, 2006; Rowe, 2011).

Green roofs also improve the quality of stormwater runoff compared with conventional roofs. Heavy metal concentrations in green roof runoff are lower than those from neighboring conventional roofs and dependent on drain pipe composition and age of green roof (Czerniel Berndtsson, 2010; Czemiel Berndtsson et al., 2006; Rowe, 2011). Czemiel Berndtsson (2010) speculated that heavy metal concentrations in runoff are not reduced, but the total amount of heavy metals coming off the roof are lower, because of water retention. However, there is some disagreement about the impact of green roofs on nitrogen levels in runoff (Czemiel Berndtsson et al., 2006; Hathaway et al., 2008). Some studies have also shown that green roofs increase phosphorus concentrations in runoff (Czemiel Berndtsson et al., 2006; Hathaway et al., 2008). Nitrogen and phosphorus levels in runoff are of greater concern on roofs that require the addition of chemical fertilizers (Czemiel Berndtsson et al., 2006; Emilsson et al., 2007; Rowe et al., 2006). The impacts of fertilizer addition on stormwater quality can be minimized, if controlled release fertilizers are used instead of easily dissolved fertilizers (Emilsson et al., 2007).

Emerging Uses of Green Roofs

Carbon Sequestration. In the recent past, there has been growing concern surrounding global climate changes, focused on temperature increases due to anthropogenic GHG emissions. The Intergovernmental Panel on Climate Change (IPCC) has published several reports outlining sources of anthropogenic GHG emissions, changes in emissions levels, and the impacts that emissions levels have, and are projected to have, on climate. One of the most recent reports states that CO_2 levels have increased by 36% in the last 250 years, half of which took place after 1970 (IPCC, 2007). The National Research Council (2010) has recently stated that atmospheric CO_2 levels reached 396 ppm as of June 2012 (ESRL, 2012), higher than any levels estimated for the last 800,000 years. This increase in GHG emissions has been shown to have a number of actual and potential impacts on climate including rises in temperature, changes in precipitation patterns and ice cover, as well as increases in extreme weather events (IPCC, 2007; NRC, 2010).

These reports led to the development of a number of policies regarding GHG emissions. One of the most notable policies is the Kyoto Protocol, which calls for a reduction in greenhouse gas emissions to 5% below 1990 emissions levels by the year 2012 (UNFCCC, 1997). The goals of the Kyoto Protocol have been met with varying success. Annex 1 countries have reduced emissions by as much as 54.7% *(Latvia) but have also increased emissions by as much as 119.1 % (Turkey) (UNFCCC, 2009). These policies have enabled the creation of emissions trading markets in which organizations surpassing reduction requirements are able to sell credits to other companies or organizations (UNFCCC, 1997). Currently, 192 nations and 1 regional economic integration organization have ratified the Kyoto Protocol (UNFCCC, 2011). For some GHGs, credits can be quite valuable in markets that trade them. Nitrogen oxide credits, for example, sold for $2800 to $4000 per ton in 2004 (Clark et al., 2005). One example is the Chicago Climate Exchange (CCX), an institution that oversees a legally binding cap and trade system for GHGs in North America (CCX, 2009). The CCX was a two phase program requiring emissions reductions of 1% per year in the first phase and emissions reductions to 6% below baseline for all members by 2010 in the second phase. Those unable to meet the reductions must purchase credits from institutions that surpass reductions (CCX, 2009). In 2011, the Chicago Climate Exchange Offsets Registry Program was launched to develop a database of verified emissions reductions (CCX, 2011). The total work of global carbon markets reached US$ 176 billion in 2011 with a total of 10.3 billion T CO_2 Eq traded (Kossoy and Guigon, 2012). There are also established trade programs for sulfur dioxide and nitrogen oxides in both Europe and the United States (Clark et al., 2006).

If companies are to trade carbon credits, they must first have an understanding of the ability of their landscapes (natural, agricultural, ornamental, at grade, or on rooftops) to sequester carbon. Carbon sequestration rates on the landscape level can be highly variable and are dependent on species diversity, plant physiological characteristics, species abundance, and climate (Kucharik et al., 2003; Matamala et al., 2008; Sandermann and Amundson, 2009; Tilman et al., 2006). Tilman et al. (2006) found that a low-input high-diversity mix of perennial herbaceous grassland species provided a greater amount of soil carbon sequestration than mixes with fewer species or monocultures. They also found increased root biomass with increased species diversity. Soil carbon losses during the conversion from forests to pasture are lower when a mix of species, rather than a monoculture, is used (Rhodes et al., 2000).

The type of plants present can impact above-ground biomass, litter quality and quantity, and root distribution and biomass, which impact carbon concentrations and the role of dissolved organic carbons (DOCs) in carbon sequestration in soils (Sanderman and Amundson, 2009). In poplar trees, mean carbon concentrations range from 42% in leaves to 50% in stems (Fang et al., 2007). This pattern of carbon content has also been shown in olive and peach trees (Sofo et al., 2005). In a forest, litter is the largest source of DOC, but in a prairie, the biologically active root zone is the dominant source of DOC (Sanderman and Amundson, 2009). There are also differences in the ability of C3 and C4 plants to sequester carbon. C4 plants sequester less carbon than C3 plants; higher proportions of C4 plants in an ecosystem result in less carbon sequestration by that system (Rhodes et al., 2000).

These physiological differences contribute to landscape level changes in carbon sequestration in both space and time. Variation in aboveground carbon has been attributed to variations in species composition (Matamala et al., 2008). Increases in soil temperature and prolonged drought have been shown to cause changes in species composition. Harte et al. (2006) showed that, a shift from forbs to shrubs resulted in fewer carbon inputs to the soil, but also lowered decomposition rates because litter shifted to more recalcitrant forms. This species shift took place under both 2°C warming and drought conditions resulting in 22 and 15% reductions in soil organic carbon (SOC), respectively. Balesdent et al. (2000) also reviewed studies that suggested similar responses to warming and drought. These results may have implications for future carbon sequestration as temperatures and precipitation patterns change because of climate change.

The age of a landscape can also affect plant physiological characteristics, and therefore carbon sequestration. Matamala et al. (2008) found that litter, microbial, and root biomass increased with age in prairie landscapes. As woody plants age, more biomass is allocated to stems, and less to leaves and roots (Fang et al. 2007), which leads to reductions in litter biomass with age. Other site conditions, such as soil properties and soil moisture content also influence carbon sequestration. Irrigation of arid lands has been shown to result in increases of both SOC and soil inorganic carbon above levels found in native soils (Wu et al., 2008). This increase may be due to differences between crop and native plant root density and structure. Drying and rewetting cycles may also be a factor effecting the protection of carbon soil pools, in part because of deabsorption of SOM (Balesdent et al., 2000). Clay contributes to the protection of soil carbon pools, by holding SOM within its particles (Balesdent et al., 2000).

Management practices impact the ability of natural and agricultural and landscape systems to sequester carbon (Balesdent et al., 2000; Fang et al., 2007; Wu, et al., 2008). Numerous studies have shown that cultivation for agriculture causes a drop in soil organic matter (SOM) (Balesdent et al., 2000). Agricultural land has a lower percent SOC than land that has been returned to grassland for at least 8 yrs at soil depths of 0 to 5 cm, but not at depths between 5 and 25 cm (Kucharik et al. 2003). Total percent organic matter showed a similar pattern and both SOC and total organic matter were lower than in adjacent pasture sites. This observation is in agreement with other studies showing lower microbial and root biomass and SOC in cultivated fields than in prairie ecosystems (Matamala et al., 2008), and a reduction in carbon when forests are converted to agricultural lands (Rhodes et al., 2000). Tillage breaks up macroaggregates in soil, which protect pools of SOM, increasing carbon mineralization (Balesdent et al., 2000). The addition of crop resides, can add SOM (Wu, et al., 2008). In no-till systems some of this SOM remains above the mineral soil, an effect which must be taken into account when studying soil carbon pools (Balesdent et al., 2000). The decay rate of SOM under no-till systems is also lower, because SOM remains protected within undisturbed soil aggregates (Balesdent et al., 2000).

Soil organic and inorganic carbon can increase in agricultural soils over many decades; however, these increases take place at depths of 10 to 60 cm and greater than 150 cm, respectively (Wu et al., 2008). Restoration of agricultural lands to prairie can also return both aboveground and SOCs to levels found in remnant prairies. The former can take as little as 14 years, but the latter requires several centuries (Matamala et al., 2008). Carbon residence times do, however, vary with climate, ecosystem, soil depth, and soil properties. High clay content, for example, promotes long-term carbon storage via adsorption to clay particles, while sandy soils tend to promote downward transport of dissolved organic carbon (DOC) (Sandermann and Amundson, 2009). In the short term, changes in SOC levels are minimal, 1 to 10 % of the carbon pool size, making them difficult to detect**.** Kucharik et al. (2003) suggest that these changes in carbon pools would be more easily detected using a soil surface layer between 5 and 7.5 cm, especially when comparing land use types. Organic carbon has also been shown to increase in constructed landscapes. Getter et al. (2007) found and increase in organic carbon from 2.33 to 4.35 % over five years in an extensive green roof.

The ornamental horticulture industry comprises a large portion of the United States economy and a large area of land for both production and planting (Marble et al., 2011). Typical ornamental planting substrate is pine bark based, with much greater carbon content than field soils (Marble et al., 2011). This material is then transferred into the ground when planted and if the plant biomass accumulation is greater than the rate of decomposition then it could be considered a carbon sink (Getter et al., 2009). Carbon sequestration of urban trees and forests has been well studied. Urban tree carbon sequestration depends on the tree species used, their growth rates and tree ages (Stoffberg et al., 2010). Stoffberg et al (2010) estimated that the 115,200 street trees in Tshwane, South Africa, would sequester 200,492 tons of CO_2 by 2032, valued at about 3 million U.S. dollars. Using remote sensing to examine urban forest cover over time in Syracuse, NY, USA, Myeong et al. (2006) estimated that148,659 tons of carbon were stored in 1999. They also found a pattern of increased carbon storage between 1985 and 1992 of 1.79 %, but a decrease between 1992 and 1999 of 0.52 %. Myeong et al. (2006) concluded that Syracuse had not undergone much urbanization in that time frame and was therefore showing relatively stable carbon storage. When compared to nearby rural forests, urban forests are a greater sink for CO_2 during the growing season, but a greater source of it during the rest of the year (Awal et al., 2010). This difference has been attributed at least in part to higher urban temperatures (Awal et al., 2010). Forest understory carbon content has also been assessed to a certain extent. Estimates of the forest understory carbon pool range from 1.0 to 4.8 t C/ha (Smith et al., 2004). It is however not clear if this would be useful in assessing ornamental landscapes.

Some barriers to putting this knowledge about carbon sequestration into practice have been discovered. These include a lack of a complete inventory of urban trees, carbon emissions reductions are not yet a goal of some municipalities, a lack of familiarity with carbon trading markets among municipal forest managers (Poudyal et al., 2010), inadequate updating of inventories over time, and a lack of standardized sampling methods (Brown, 2002). There are however guidelines available to help urban forest managers and those hoping to sequester CO_2 though urban tree projects calculate both carbon sequestered and carbon emissions (eg. McPherson and Simpson, 1999). Current carbon markets also complicate the issue of carbon sequestration in forests and potentially urban trees and ornamental landscapes. Currently forest carbon stocks are purchased outright, and considered permanent, limiting flexibility in management practices and restricting entry into the market by small forest owners (Bigsby, 2009). Limiting management practices puts a large burden of liability on the forest owner in the event that the land is shown not to contain the carbon sold, for any reason including natural disaster (Bigsby, 2009). Small forests can change hands frequently and different owners have differing ideas about what management practices are best (Bigsby, 2009). Management practices also need to be a factor in the overall assessment of net carbon sequestered. Nowak et al (2002), suggest a last positive point (LPP), a point in time where carbon emitted to manage a urban trees exceeds that which is sequestered by those trees. The length of time it takes to reach this point depends on the extent of management, the extent management relies on carbon emitting tools, and the fate of removed tree material and therefore the rate at which that removed carbon is returned to the atmosphere. More intensive management and faster return of removed carbon to the atmosphere results in achieving the LPP in fewer years (Nowak et al., 2002). Ornamental landscapes change hands frequently and are highly managed for aesthetics using carbon emitting tools such as lawn mowers and leaf blowers. Extraneous detritus, such as grass clippings, fallen leaves, and dead flowers, are often removed and changes in landscape design could drastically alter the carbon stock.

Bibsby (2009) suggests the use of a carbon banking system to address forest management issues, which could apply to other ornamental landscapes. Under such a system owners of carbon stocks deposit carbon on a short term basis and carbon individuals or corporations seeking to offset carbon emissions borrow carbon (Bigsby, 2009). A better understanding of carbon sequestration in ornamental landscapes incorporating shrubs, perennials and other ornamental species would be necessary to apply those carbon assets to any carbon market. There is currently little such information available in the literature (Marble et al., 2000). Another complicating factor has also been pointed out, who gets the credit for the carbon sequestered? The pine bark mulch used as potting substrate is an industry byproduct of forestry operations and Marble et al. (2000) suggest that credit will depend on what the alternative fate of the pine bark would have been and if the forestry industry has already made a financial gain from the sale of the pine bark to the ornamental horticulture industry.

Rooftops converted to green roofs offer spaces in which sequestration of CO_2 and other GHGs can take place. As these areas are relatively undisturbed and can have recorded roof life spans of up to 50 years (Kohler and Keeley, 2005) they are potential short- to moderate-term sinks. If just 10% of roofs in Chicago, Illinois were green, they are estimated to sequester between 445 and 15267 tons NO_x per year, depending on the plant species used (Clark et al., 2005). Although this sequestration capacity represents only 0.46 to 15.89 % of total emissions for the city of Chicago, it increases with increasing green roof area and could be used in emissions trading programs (Clark et al., 2005). Economic benefit from such programs could offset the high initial cost of installing a green roof, one barrier to their widespread construction by enabling faster returns on the initial investment (Clark et al., 2005; Clark et al., 2006).

However, little research has been done to quantify the carbon sequestration potential of green roofs. There has also been limited research on carbon sequestration in ornamental planted landscapes, which could be a closer approximation to green roof landscapes than the agricultural or forested landscapes discussed in the literature. This, in combination with the highly variable ability of species to sequester GHGs (Clark et al., 2005), illustrates the need for further research that not only quantifies sequestration by a whole roof, but also sequestration by individual species, in order to develop of species mixes that optimize sequestration.

Getter et al. (2009) found that extensive green roofs store an average of 162 g C/m^2 (1.62 t C/ha) in aboveground biomass, with variation due to roof age and substrate depth. Further examination of belowground biomass and substrate showed that the whole extensive green roof system examined sequestered 375 g C/m^2 (3.75 t C/ha) (Getter et al., 2009). This was in addition to the initial carbon content of the green roof substrate. Although substrate carbon content was found to be comparable to that of other ecosystems, the above-ground and root biomass was found to be lower than expected based on the literature on vascular plants. Getter et al. (2009) speculated that this may be due to the age of the plants in the study, and differences between the physiology of succulents used on green roofs and the plants used in previous research on forests and agriculture. Higher temperatures on rooftops may also contribute to faster oxidation, affecting carbon sequestration. Rugh et al. (2010), have taken another approach to estimate the carbon sequestration of a large green roof over time. Using the results of Getter et al. (2009), they grouped the plant species found on the Ford Dearborn truck plant and estimated whole roof aboveground biomass sequestration from species abundance and coverage data generated in surveys taken in 2009 and 2010. They estimated 194.8 and 195.1 g C/m^2 (1.95 t C/ha,respectively) for spring 2009 and summer 2010, respectively stored in aboveground biomass (Rugh et al., 2010), which were very similar to the 196 g C/m^2 (1.96 t C/ha), value sampled in 2006 by Getter et al (2009). This suggests that the carbon content of a green roof is stable over time (Rugh et al., 2010), and there is a limit on the amount of carbon a roof is able to sequester.

The ability of green roofs to sequester carbon will also be affected by the embodied energy or carbon of materials used in the construction, and how that might differ from the conventional roof alternative. Getter et al. (2009) estimated the embodied carbon content of green roofs to be 6.6 kg C/m^2. This includes typical root barrier, drainage layer, and substrate of heat expanded slate and sand and was 6.5 kg C/ m^2 larger than the estimated embodied carbon for a traditional roof. This embodied carbon must be accounted for when considering the value of green roof carbon sequestration, especially considering that it is much greater than the amount of carbon contained in substrate and plant biomass (Getter et al., 2009; Rugh et al., 2010). Those estimates do not, however, take into account annual emissions avoided through the energy saving benefit of green roofs. According to Getter et al. (2009) it will take 9 yrs to offset the carbon debt of green roof materials using emissions savings.

There is also the issue of carbon credit quality. The quality of a carbon credit depends on a set of criteria, which also vary with organization. Poudyal et al. (2011) compiled several lists of criteria and found additionally, baseline establishment, use of real or actual emission reduction, quantification and monitoring, verification, ownership, leakage, permanence, regionalist, and co-benefits were of importance. The authors found that urban forests often met these requirements. In ornamental landscapes, permanence is of particular importance. In the case of urban forests, these trees meet the requirements as they are not harvested and many municipalities have plans in place to manage tree loss due to disease or natural disaster (Poudyal et al., 2011). Green roofs have an estimated lifespan of 40 to 60 yrs (Carter and Keeler, 2008; Lee, 2004). Compare this to the 30 to 40 yr time frame of studies on urban tree survival (Stoffberg et al., 2010) and green roofs may also be considered to meet the permanence requirement of a quality credit. Other ornamental landscapes, may not however meet the criteria of permanence. This may depend on the lifespan of ornamental species used, the ability of annuals to self-seed and maintain their populations, and the frequency that ornamental areas are re-landscaped. These issues draw into question the quality of potential carbon credits from ornamental landscapes and highlight areas of needed research.

Urban Agriculture. Global population, currently at 6.99 billion (USCB, 2012), is continuing to rise, with a projected increase to 9.3 billion in 2050 (USCB, 2009). This estimate has resulted in speculation about whether agricultural food production will be able to keep up with a growing demand (Peters at al., 2009). In 2007 the United Nations Department of Economic and Social Affairs, Population Division predicted that 50 % of the world's population would live in urban areas, and that this percentage would continue to increase (UNDESA, 2007). The growth of urban centers raises concern about ensuring access to food, both in the ability of a region to produce and ship adequate food supplies to the urban center and in the ability of urban residents to afford adequately nutritious food (Enete and Achike, 2008; Graefe et al., 2008; Peters et al., 2009; Vagneron, 2007; van Averbeke, 2007). Many turn to urban agriculture to address these issues. Urban agriculture is, however, not without problems (Agbenin et al., 2009; Enete and Achike, 2009; Graefe et al., 2009; Thornton, 2009; Vagneron, 2007; van Averbeke, 2007). Green roof technology is one possible method of urban food production that would address some of these problems as is discussed further in chapter 1.

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CAPTER ONE

The role of green roof technology in urban agriculture, by Leigh J. Whittinghill and D. Bradley Rowe Renewable Agriculture and Food Systems, FirstView Article (August 2011), pp. 1-9

Abstract

Urban agriculture is a global and growing pursuit that can contribute to economic development, job creation, food security, and community building. It can, however, be limited by competition for space with other forms of urban development, a lack of formalized land use rights, and health hazards related to food contamination. The use of green roof technology in urban agriculture has the potential to alleviate some of these problems, without adversely affecting the benefits provided by urban agriculture. It would not only enable the use of land for development and agriculture, but may facilitate the formation of formal space and water use agreements and enable redistribution of ground level resources among urban farmers. This could decrease the use of contaminated land and water at ground level and alleviate health concerns. Before green roof technology can be incorporated into urban agriculture on a larger scale, installation costs must be reduced, roof weight limitations should be assessed, and appropriate management practices developed which will ensure that the benefits of green roofs, such as energy savings and storm water management, are still provided to urban communities.

Introduction

In recent years, the importance of green space in urban areas has been changing. A new vision of urban centers incorporates more green space, such as parks (Nowak, 2006), and a more human friendly environment mixing traditional urban centers of industry, commerce and residence with food production (Nugent, 2002; de Zeeuw et al., 1999). Implementation of this vision has been facilitated by the introduction of more environmentally friendly technologies and the introduction of policies and programs which that promote their use (Cheney, 2005; City of

Chicago, 2006; City of Portland, 2009; Kula, 2005; Lipton, 2005). One such technology being incorporated into development is green roofing.

Definition of green roofs. Green roofing is a technology enabling growth of vegetation on rooftops, effectively replacing green space lost during building construction. Conventional green roofs generally consist of a number of layers including a root barrier to prevent damage to the underlying structure; a drainage layer to facilitate the removal of excess water; a filter fabric to prevent the drainage layer from clogging with media; growing media; and vegetation (Getter and Rowe, 2006). Others may be composed of growing modules or vegetated mats. Green roofs vary in depth of growing media and vegetation, but are generally broken up into two categories: extensive (those with less than 15 cm of media) and intensive (those with more than 15 cm of media) (Kula, 2005). Extensive roofs are usually planted with ground cover or succulent species that require little maintenance after establishment, while intensive roofs can support herbaceous perennials, shrubs and even trees (Dvorak and Voder, 2010; Getter and Rowe, 2006) but typically require continued inputs. Design and plant selection depend on the purpose of the project and the environmental benefits to be achieved. Uses of green roofs range from functional storm water and energy management roofs, to park like amenities open to the public, to food production.

Factors determining plant survival include media composition and depth (Getter and Rowe, 2009; Rowe et al., 2006), incoming solar radiation (Getter et al., 2009), climate, and most importantly soil moisture (Durhman et al., 2006; Emilason, 2008; Monterusso et al., 2005). Insufficient moisture can be remedied by altering media composition and depth or with irrigation if available. Growing media used on commercial green roofs are often engineered and comprised mostly of lightweight materials such as heat expanded slate or shale (Getter and

Rowe, 2006). Media composition depends on manufacturer and available materials, but it is designed to be lightweight while maintaining the ability to support plant life. Organic matter content may vary and is beneficial for plant growth, but when it decomposes it may leach nutrients resulting in runoff water quality issues and is inconvenient to replace. Economics dictate that substrate composition will depend on materials that are locally available and can be formulated for the intended plant selection, climatic zone, and anticipated level of maintenance.

Benefits of green roofs. Use of green roofs in urban development has been shown to provide a number of benefits including reduced air and noise pollution, carbon sequestration, increased habitat and biodiversity, increased roof lifespan, storm water retention, energy savings and mitigation of the urban heat island (Alexandri and Jones, 2008; Barrio, 1998; Czemiel Berndtsson, 2010; Getter and Rowe, 2006, Getter et al., 2007; Getter et al., 2009; Loder and Peck, 2004; Monter. Computer modeling predicts that an increase in green roof area, as could take place with the technology's incorporation into urban agriculture, will amplify these benefits (Bass et al., 2003). Moreover, the introduction of green roofs to city development plans could promote infill development (the redevelopment of vacant areas within urban centers) and reduce spending on the development of new infrastructure such as roads and sewer lines (Loder and Peck, 2004). Although infill development largely benefits municipalities and companies, expansion of the green roof industry would increase employment and economic growth in urban centers benefiting populations which typically turn to urban agriculture.

Energy savings (Fang, 2008; Sailor, 2008; Santamouris et al., 2007; Wong et al., 2007) and mitigation of the urban heat island (Alexandri and Jones, 2008; Bass et al., 2003; Harlan et al, 2006; Johnson and Wilson, 2009; Memon et al., 2008; Wong et al., 2003) in particular have great practical benefit to poorer communities who are most likely to benefit from urban agriculture. Green roofs can reduce energy consumption of a building from 2 to 39% (Sailor, 2008; Santamouris et al., 2007) and between 12 and 87% for the top floor (Santamouris et al., 2007) during the summer. These reductions are primarily due to reducing the amount of direct solar radiation that reaches the roof and the amount of heat transferred into the building (Fang, 2008; Wong et al., 2007). The extent of the reduction is dependent on the extent of vegetative cover on the roof (Fang, 2008; Sailor, 2008; Wong et al., 2003), the existence of other insulation (Santamouris et al., 2007), the thickness of the green roof media, irrigation of the roof and climate (Sailor, 2008). Energy savings during the winter are negligible in warm climates, but can be seen in cooler climates (Sailor, 2008; Santamouris et al., 2007). Energy savings in very humid climates are also expected to be lower due to reduced evapotranspiration and the associated cooling effects (Alexandri and Jones, 2008).

Green roofs have been shown to reduce ambient temperatures (Wong et al., 2007), an effect which is projected to increase with increasing roof surface area and the inclusion of green walls (plants grown on walls using a variety of training and planting systems) in urban development (Alexandri and Jones, 2008; Bass et al., 2003). Modeling predicts a corresponding reduction in urban temperatures and increase in thermal comfort (Alexandri and Jones, 2008; Bass et al., 2003). The end result of reduced temperatures and therefore energy use is a reduction in the use of conventional air-conditioning (Alexandri and Jones, 2008; Santamrouris et al., 2007). This would benefit low income neighborhoods for two reasons. Urban neighborhoods with higher summer temperatures than surrounding urban areas are correlated with lower incomes, higher poverty rates (Harlan et al., 2006) and impoverished individuals aged 65 and older (Johnson and Wilson, 2009) in cities such as Phoenix, AZ and Philadelphia, PA. These individuals are more at risk to environmental hazards such as extreme heat events due to a lack of resources enabling them to cope with the hazards, such as air-conditioning (Harlan et al., 2006). Implementation of green roofs would not only reduce energy bills in such neighborhoods, but could also reduce the occurrence of extreme heat and the need to air-condition in the summer time, freeing up limited funds for other uses and improving the quality of life of individuals in these at risk areas and populations.

Figure 1.1. Vegetable production on a green roof in East Lansing, MI

Food production in an urban setting. Food production can be added to the benefits provided by green roofs (Loder and Peck, 2004; Arpels et al., 2005) (Figure 1.1) and expanded through the technologies incorporation into urban agriculture. Urban agriculture is defined as horticultural, agricultural, or farming activities carried out on plots of land in and around urban centers (Enete and Achike, 2008; Graefe et al.., 2009; Vagneron, 2007). Individuals in urban centers around the world participate in urban agriculture for reasons, such as poverty, unemployment, food insecurity (Nugent, 2002; van Averbeke, 2007), high prices of market food, income or asset diversification and supplementary employment (Nugent, 2002). These motivational factors (Enete and Achike, 2008; Graefe et al., 2009; Hu and Ding, 2009; Nugent, 2002; Peters et al., 2009; Vagneron, 2007; van Averbeke, 2007; de Zeeuw et al., 1999); limitations such as land availability, land use and ownership rights, physical and economic access to inputs and potential food contamination (Agbenin et al., 2009; Enete and Achike, 2008; Graefe et al., 2009; Thornton, 2009; Vagneron, 2007; van Averbeke, 2007); and geographic and climatic factors unique to each urban center shape urban agriculture (Enete and Achike, 2008; Nugent, 2002; Vagneron, 2007; de Zeeuw et al., 1999). It is likely that a number of these limitations could be alleviated through the use of green roofs, while maintaining the benefits expected by urban farmers. Currently, policy is under reform in a number of cities worldwide resulting in accommodations for urban agriculture (de Zeeuw et al., 1999). These policy changes present an opportunity and could be guided to include farming on green roofs and expedite the inclusion of green roofs and other alternative technologies in urban farming with substantial benefit to urban populations.

Despite the possible benefits from incorporating green roof technology into urban agriculture, there are a number of potential issues which must be addressed. These include installation and maintenance costs, weight limitations, media composition and depth, cultural practices, potential water quality issues of effluent, and how food production would influence the other known benefits attributed to green roofs. These are not only factors that may limit the use of green roofs, but would also limit their viability for widespread use in urban agriculture.

Further research and innovation may present solutions to these problems. The goal of this review is to examine some of the possible benefits and barriers to incorporating green roof technology into urban agriculture. In doing so we shall first examine the current state of urban agriculture and then introduce potential benefits or limitations of using green roof technology. Due to the lack of published studies on the subject we will also discuss future research needs. We have therefore broken the review up into sections containing common themes; economic benefits and food security, economic barriers, access to resources and policy, human health, and environmental health concerns.

Economic improvement and food security

Economic development brought about by participation in urban agriculture comes in a variety of forms including the supplementation of family income, job creation, and freeing up funds previously used to purchase food. Crop choice and scale affect the extent to which urban agriculture contributes to the income of a household (Graefe et al., 2009; Nugent, 2002; Vagneron, 2007; van Averbeke, 2007). Rice, for example, is a staple in many parts of the world and can provide income security for an urban farmer's household (Vagneron, 2007), but production of vegetables may yield higher market prices (Graefe et al., 2009; Vagneron, 2007). Animal husbandry, another form of urban agriculture, can provide high profits (Graefe et al., 2009; Nugent, 2002; Vagneron, 2007), but may require much higher investments (Vagneron, 2007). In some cases social capital can be generated by a household, by giving away food that could not be sold (Nugent, 2002). The impact of urban agriculture on employment is highly variable, depending on the economic status of urban farmers (Graefe et al., 2009; Nugent, 2002). For households in both developing and developed countries that do not produce food for sale, or sell only their excess produce, urban agriculture frees up funds for other uses (Enete and Achike, 2008; Nugent, 2002; Vagneron, 2007; van Averbeke, 2007). The prevalence of urban agriculture increases when poverty increases and when costs of purchasing food surpass that of growing it (Nugent, 2002). This can be an important measure in stretching household budgets, allowing for the purchase of other items (Nugent, 2002; van Averbeke, 2007) or some economic freedom for women where household budgets are male-controlled as was found in Pretoria, South Africa (van Averbeke, 2007). In addition, economic concerns are an incentive for consumers who assume that purchasing local produce increases economic returns to local farmers through shortened supply chains and better market accessibility (Hu and Ding, 2009; Peters et al., 2009).

Food security, the second major driver of urban agriculture, is affected by both quantity and quality of food available to a household. Even in locations where urban agriculture does not contribute significantly to employment, food security is of major concern to urban farmers (Nugent, 2002). Food in the U.S. is shipped 2080 km (1300 mi) from to consumer, but this could be reduced to 49 km with re-localization of the food (Peters et al., 2009). It has been estimated that under ideal conditions the agricultural products of the entire state of New York could not supply the agricultural needs of more than 55% of New York City (Peters et al., 2009). This suggests that providing adequate food supplies for urban centers with growing populations may not even be possible on a regional scale and costs associated with shipping may affect the food security of the urban poor. Producing agricultural goods within urban centers is one method of reducing the ecological footprint of urban centers (Peters et al., 2009; de Zeeuw et al., 1999) and ensuring urban dwellers access to food. Food insecurity, or the lack of access to adequate food for an active and healthy life (Alexandri and Jones, 2008) is not just a problem in the developing world, but in the United States as well (Enete and Achike, 2008; Nugent, 2002;

Widome et al., 2009) (Figure 1.2). Food insecurity can be temporary or chronic (de Zeeuw et al., 1999) and is associated with a variety of problems in adolescents, who are at higher risk than young children (Widome et al., 2009). A perceived or actual need to improve food security and a lack of ability to rely on food from rural areas can result in the use of urban agriculture (Graefe et al., 2009; de Zeeuw et al., 1999), which has been shown to improve the quantity and quality of food available to low income urban households under a variety of conditions (Enete and Achike, 2008; Graefe et al., 2009; Nugent, 2002; Widome et al., 2009; de Zeeuw et al., 1999).

Figure 1.2. . A community garden in Detroit, MI.


Figure 1.3. An herb garden on a green roof in Grand Rapids, MI.

Green roofs are already utilized to improve the economic circumstances and food security of urban farmers (Figure 1.3). EcoHouse, in St. Petersburg, Russia is an example of a rooftop garden project which provides jobs to and increases cash flow among individuals living within the apartment complex (Arpels et al., 2005). The project also provides those residents with a reliable source of vegetables (Arpels et al., 2005). Another example is the green roof of the Fairmont Hotel in Vancouver, a portion of which is devoted to a kitchen garden, saving the hotel approximately $30,000 a year (Loder and Peck, 2004). The rooftop garden on Earth Pledge's New York office is used not only as a source of food, but as a promotional tool for the group's organic local produce campaigns (Cheney, 2005; Loder and Peck, 2004). Similar community garden projects have been developed in other cities, such as the Multnomah County Green Roof Project in Portland, OR (King, 2004) and several community scale gardens in Chicago, IL

(Coffman and Martin, 2004). A green roof at Trent University in Peterborough, Ontario is producing vegetables for a local restaurant, The Seasoned Spoon Café, which was started as a healthy fast food alternative (Blyth and Menagh, 2006).

Economic barriers

Economic barriers to urban agriculture include inadequate access to or knowledge about markets (Nugent, 2002) and insufficient labor (Bass et al., 2003; Nugent, 2002), inputs such as fertilizers (Vagneron, 2007), quality seeds (Graefe et al., 2009), and credit or subsidy for startup costs or inputs (Enete and Achike, 2008; Graefe et al., 2008; Nugent, 2002; Vagneron, 2007), the latter three of which are of more concern in developing nations. These barriers are due to limited resources of urban farmers and will not be affected by the introduction of green roof technology to urban agriculture. An additional barrier introduced by the use of green roof technology is the cost of green roof installation and maintenance.

Installation of a green roof can be \$32/m^2 more expensive than a conventional roof for roof structure alone (Wong et al., 2003). Installation of green roof systems can vary from two to six times more expensive than conventional roof systems depending on the design of the roof system (Wong et al., 2003). Factors that impact the cost of a green roof include ease of access for installation, structural integrity of the building, type of drainage system, depth and composition of media, inclusion of an irrigation system and the use of a modular, mat or conventional built-up continuous roof system (Rowe and Getter, 2010). Maintenance costs of a green roof also depend on roof design, as intensive roofs tend to require more care than extensive roofs. Maintenance of the roofing layers themselves is comparable to that of a conventional roof due to the longer life span of green roofs (Wong et al., 2003).

Tapping into incentive programs such as those used in Portland, OR (City of Portland, 2009) and Chicago, IL (City of Chicago, 2006) which provide reductions in storm water removal fees and grants to help subsidize installation may help. Other programs, such as those geared toward improving the availability of fresh fruits and vegetables in urban centers and improving healthy eating habits in urban youth may also be sources of funding. It is also possible that locally made materials could be used to construct green roofs, reducing the cost of installation, but generation of policy promoting the use of green roofs and subsidizing their installation will be of greater importance in low income areas than in high income areas. Evaluation of locally available materials would also be necessary to determine both their suitability and their impact on green roof installation costs.

Access to resources and policy

Availability of land, especially land of adequate quality, is the main obstacle affecting urban agriculture (Nugent, 2002; de Zeeuw et al., 1999). Land scarcity and uncertainty in maintaining access to available land are due to competition with other development uses, primarily building construction (Graefe et al., 2009; Nugent, 2002; Vagneron, 2007). These other uses are often more economically profitable and are therefore preferred by land owners (Thornton, 2009; van Averbeke, 2007; de Zeeuw et al., 1999). Land use and investments in urban agriculture by urban farmers are impacted by resource use rights. Under current systems there are often no formal leasing agreements between land owners and urban farmers cultivating vacant lots (Nugent, 2002). Rights of urban farmer are often minimal (de Zeeuw et al., 1999), uncertain (Thornton, 2000), and frequently transient due to changing land uses and termination of informal use agreements (Thornton, 2009; van Averbeke, 2007). Lack of formal agreements over water use rights has led to conflict between municipalities and urban farmers (van Averbeke, 2007).

Incorporation of green roofs into new development would increase the potential agricultural area and remove competition with urban development that reduces willingness of urban farmers to invest in urban agriculture (Nugent, 2002; Vagneron, 2007). Currently, flat rooftops comprise as much as 85% of the roof area in downtown and commercial areas (Carter and Jackson, 2007). In larger urban areas this could add up to a great deal of space and potential for productive use if these existing roofs were retrofitted into green roofs. Buildings must, however have the structural integrity to support the added weight in a worst case scenario, regardless of whether roofs are designed new or retrofitted (Kortright, 2001). Some existing roofs may not be suitable for retrofitting without considerable costs incurred in structural support. Many flat roofs have load capacities of only 146 kg/m^2 ($30/ft^2$), which could be exceeded by as little as 7.6 cm (3 in) of growing media (Dillion, 2010). This means that the flat roof area of existing buildings which could be used for urban agriculture is not accurately represented by the flat roof area of a city. More information on what roofs can support the additional weight of a green roof and the minimum depth of media necessary for agricultural production will enable more accurate estimates of how much roof area could be used. Despite these limitations, land owners could take advantage of this potential, enabling them to utilize more profitable development and then generate secondary profits through rental agreements with urban farmers.

Development of flat roof space into agriculturally productive areas could facilitate formalization and standardization of rental, leasing, or use agreements between land owners and urban farmers. Access to roof space is limited and would require urban farmers to negotiate with building owners to gain access to the green roof space. This would be a reversal of the current use of vacant lots for urban agriculture, whose absent owners are unaware of agricultural activities or unwilling to take measures to keep urban farmers off the land (Nugent, 2002; de Zeeuw et al., 1999). Although this could create problems for urban farmers if green roof owners are unwilling to rent the space due to zoning or building code issues that might arise (Sutton, 2009, UNDESA, 2007), it could also empower urban farmers. Formal, legally binding use arrangements would grant urban farmers recourse should the green roof owner break the agreement. Such formal and empowering leasing agreements could also encourage farmers to increase investments in urban agriculture, increasing productivity and food security. Urban farmers with informal arrangements do not currently have this level of power and security (Thornton, 2009; van Averbeke, 2007; de Zeeuw et al., 1999). Formalized rental and leasing agreements could easily be extended to include access to the buildings water supply. This would be greatly beneficial to those farmers who have expressed willingness to pay for clean water where no clean water source currently exists (Graefe et al., 2009), but will increase the costs of farming for most urban farmers. Rainwater capture from an unused portion of the roof may also provide an added source of clean water for irrigation.

There are however, two additional potential outcomes of rental agreements for the use of green roof space. First is the exclusion from farming and water resources of resource poor urban farmers unable to pay rent for green roof space. Second is the reallocation of ground level space and water sources currently used by farmers able to pay for rental agreements. The former could result in greater problems associated with poverty and food security in urban areas, but the latter could grant a larger number of urban dwellers access to land and water and therefore the economic opportunities and additional food security provided by urban agriculture. If the latter is the outcome, it would mean a better quality of life for a greater number of urban dwellers. This will be of particular importance as populations become increasingly urban both worldwide and in the United States (USCB, 2009; van Averbeke, 2007; Zhuang et al., 2009) and doubts about the ability of rural areas to agriculturally support these growing urban populations also increase (Peters et al., 2009; van Averbeke, 2007; Widome et al., 2009).

Human health concerns

Access to fertilizers is especially important as space limitations in urban agriculture require more intensive farming and greater fertilizer use per area than rural areas (Enete and Achike, 2008). Often resource poor urban farmers will use inexpensive and easily accessible fertilizers, such as manures or municipal wastes, which can lead to an increase in soil heavy metal and pathogen concentrations (Agbenin et al., 2009; Enete and Achike, 2008; Graefe et al., 2009; Sharma et al., 2009; Srinivas et al., 2009). Heavy metal and pathogen contamination of food is the primary human health concern associated with urban agriculture. Sources of contamination include soils in which crops are grown, water used for irrigation, and air pollutants. In many cases the land most readily available to urban farmers is contaminated with heavy metals from a variety of industrial and mining sources, which can lead to contamination of the agricultural products (Agbenin et al., 2009; Hu and Ding, 2009; Srinivas et al., 2009). In addition, resource poor urban farmers often cannot afford to pay for clean irrigation water even if a source exists (Graefe et al., 2009; Nugent, 2002; Vagneron, 2007). Atmospheric deposition of contaminants during production, transportation and marketing of produce also leads to elevated levels of heavy metals (Hu and Ding, 2009; Sharma et al., 2009; Vousta et al., 1996; Yang et al., 2009).

The extent to which heavy metal contamination affects safety of vegetables depends on several different factors, including the vegetable species, the part of the plant which is eaten, and the type of heavy metal (Arora et al., 2008; Sharma et al., 2009; Srinivas et al., 2009; Yang et al., 2009). On average, fruit vegetables accumulate lower quantities of heavy metals than leafy or root vegetables (Arora et al., 2008; Srinivas et al., 2009; Yang et al., 2009). Leafy vegetables are a major source of heavy metal dietary intake (Sharma et al., 2009), due to high rates of translocation, transpiration and growth as well as high surface area in close proximity to contaminated soil and irrigation splash (Srinivas et al., 2009). High surface area vegetables, such as cauliflower (Vousta et al., 1996), and those that spend more time in the field (Yang et al., 2009) are also known to accumulate higher concentrations of heavy metals through atmospheric deposition. Dietary intake of heavy metals can lead to accumulation in the human body because they are non-biodegradable (Chambria and Moyo, 2009), causing their negative effects to become apparent only after years of exposure (Chambria and Moyo, 2009; Sharma et al., 2009). Among resulting health problems are a variety of cognitive disruptions (Chambria and Moyo, 2009; Emilsson et al., 2007), nervous, cardiovascular (Emilsson et al., 2007; Srinivas et al., 2009; Vousta et al., 1996), kidney, bone and liver (Srinivas et al., 2009; Vousta et al., 1996) diseases as well as cancer (Chambria and Moyo, 2009). Although these are more common problems in developing countries, contamination of food produced in urban areas by heavy metals, such as lead, can take place in developed countries.

The use of green roofs in urban agriculture also has the potential to reduce health concerns. Green roofs have the potential to reduce use of contaminated land in urban agriculture due to the nature of their construction. In most cases, the media in which vegetables would be grown on green roofs is engineered instead of using local soils, so initial contamination will be minimal. Green roof media are also less likely to accumulate heavy metals than ground soils due to high permeability and low cation exchange capacity which results in leaching of nutrients (Czemiel Berndtsson et al., 2006) and heavy metals (FLL, 1995) into runoff water. This tendency for leaching would reduce the likelihood of vegetable contamination on green roofs if contaminated sources of water or fertilizers are used. Rental and water use agreements will also facilitate more wide-spread use of uncontaminated water sources for irrigation. Atmospheric deposition of contaminants may also be reduced during the production phase. It has been suggested that distance from the source of pollutants impacts the extent of heavy metal contamination due to atmospheric deposition (Vousta et al., 1996). Most green roofs are several stories high, increasing the distance between crop production and such sources of pollution as major roadways and highways.

In addition to food contamination, concerns about urban agriculture include health problems due to improper handling of agrochemicals and urban waste, a potential increase in pests such as rodents and flies which can contribute to the spread of diseases and the transmission of diseases from livestock to humans due to improper animal husbandry techniques (de Zeeuw et al., 1999). Although these concerns may be avoidable through proper practices, they promote negative perceptions of urban agriculture. Formalized leasing agreements may provide greater oversight of agrochemicals and urban waste used in urban agriculture. Leasing agreements could include specifications for what, if any, agrochemicals or urban wastes can be used on the green roof, how they should be stored and used, and the consequences for the urban farmer if the specifications are not followed resulting in human injury or a health hazard. In some countries organizations may already be in place which could monitor such agreements, such as the Occupational Safety and Health Administration (OSHA) in the United States. It is unlikely that the use of green roofs in urban agriculture will affect the keeping of large livestock which would be impractical on rooftops.

Environmental health concerns

Despite the costs, urban farmers are currently producing vegetables on green roofs in natural soils and composts at a media depth 17.8 to 45.7 cm (7 to 18 in) deep (GRC, 2011). This practice potentially creates several problems including the added weight to the roof, consistency of growing media, potential nutrient loads polluting effluent that discharges into our waterways from fertilizers and as compost decomposes, and the logistical practicality of adding compost every year on a roof several stories above the ground.

Water quality of runoff is another concern as nutrient leaching could cause problems downstream. Composition of the growing media is one aspect of this problem. Most commercial green roof media are formulated within the guidelines of the German FLL (Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau) standards (Hathaway et al., 2008). Years of experience has resulted in media that possess the chemical and physical properties to support plants, yet are light weight, coarse enough to allow drainage at shallow depths, can be replicated, and limit nutrient runoff when guidelines are followed. Natural soil is always variable and the addition of compost can lead to runoff quality issues. Even so, commercial green roof media generally contain about 15 to 20% organic matter which can result in nutrient loading (Czemiel Berndtsson, 2010; Rowe, 2011; USEPA, 2009). Researchers in North Carolina (USEPA, 2009) found that concentrations of both N and P decreased with decreasing percentages of compost in the media. These results emphasize the point that growing media can have an immense effect on the quality of effluent. In addition, applications of fertilizers and pesticides to ensure plant growth can be very detrimental to water quality (Czemiel Berndtsson et al., 2006; Rowe, 2011). This is especially true for soluble fertilizers applied in liquid form (Czemiel Berndtsson et al., 2006).

Studies performed on green roofs with conventional media have shown that nutrient leaching can initially be a problem, but overall, they can have a positive effect on water quality (Heilman et al., 1996; Rowe, 2011). The initial nutrient load likely is due to decomposition of organic matter that was incorporated into the original mix. Once established, and the organic matter reaches an equilibrium, vegetation and substrates can improve water quality of runoff by absorbing and filtering pollutants (Rowe, 2011). The effect of plants and their root systems was evident when effluent from an unplanted green roof containing media had higher concentrations and totals of N and P than effluent from planted roofs (Heilman et al., 1996).

There is also the question of how much fertilizer is necessary to maintain agricultural productivity in green roof media. Experimentation has shown that non succulents grown on green roofs require either additional organic matter in the media, or fertilization (Rowe et al., 2006). The relatively high levels of fertilizer that may be necessary to produce vegetables could lead to high levels of nutrient leaching. Which begs the question, are we trading the benefits of local food production for decreased water quality? If nutrient loading does turn out to be a problem, then green roofs could be coupled with other low impact development practices such as rain gardens and bioswales (landscaping techniques designed to manage storm water), although these practices are not always possible in dense urban settings. This highlights the need to develop and use green roof growing media and cultural practices that minimize leaching of nutrients while still providing adequate physical and chemical properties for plant growth.

Conclusions

In addition to previously mentioned research needs, there are several areas where research on the use of green roof technology in urban agriculture is necessary before wide scale use of the technology can be implemented. First, determination of what crops are suited to growth in green roof media will be necessary. Little is known about how growing vegetables on green roofs will impact the environmental benefits provided by green roofs. Many of the benefits are directly related to the amount of coverage achieved by the vegetation and the leaf area of the vegetation (Heilman et al., 1996). The coverage that would be achieved by vegetables will be very different than that of the ground covers and perennials traditionally used on green roofs because they are typically cultivated in rows. In addition, vegetable gardens would be replanted every year, whereas, typical green roofs are populated with perennial species. Research on how this difference will impact energy savings and storm water retention, for example, will enable better assessment of this use of green roofs in areas where these benefits are of particular importance.

The effects of other environmental factors on crops, such as exposure to higher winds, should be determined for optimum crop selection. Although pollinators have been seen and kept on green roofs, an understanding of the efficiency and quality of pollination of vegetable plants on green roofs would enable better decision making about which crops to grow and the necessity of bee keeping on vegetable growing green roofs. Finally, economic evaluation of different crops may generate more information on how much economic impact this form of food production could have on both a small and large scale.

The incorporation of green roof technology into urban agriculture maintains the economic and food security benefits of urban agriculture while eliminating some of the many difficulties faced by urban farmers around the world. The ideal case, where formalized use agreements with building owners and oversight by municipal authorities ensures greater space availability and healthier produce is however only possible through the cooperation of all parties involved, something which may be difficult in areas where urban agriculture is viewed in a particularly negative light. The formalization of use rights required by use of green roof space by urban farmers represents an opportunity for farmers to achieve guaranteed access to quality land and irrigation water, providing security for their agricultural pursuits. For land and building owners, the formalization of use rights represents an opportunity to achieve greater economic success and some degree of oversight over the activities taking place. This combination of economic opportunity and oversight may have the added benefit of improving land and building owners' attitudes toward urban agriculture, which could expedite policy reform. Municipal involvement will enable new insights into the benefits of urban agriculture and understanding the ways in which its negative impacts can be minimized.

The process, though difficult, could be made easier through the establishment of policy friendlier to urban agriculture, incentive and subsidy programs for the installation of green roofs, and research into reducing the initial cost green roofs and minimizing the inputs necessary for productive agriculture on green roofs. The resolution of these issues will further enable a future in which urban areas are greener and healthier places to live. This future could utilize ideas about development that incorporate green space in the forms of green roofs, parks or agricultural plots, enabling a closer connection with nature and the production of food with the benefit of increased food security, especially for the urban poor.

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CHAPTER TWO:

Evaluation of vegetable production on extensive green roofs

Abstract

Rooftop vegetable gardening is a production system in urban agriculture based on green roof technology. In order to broaden the scope of this practice, the use of relatively shallow substrate depths must be explored since most existing urban flat roofs are not structurally strong enough to support much added weight. In this study, vegetables grown on a roof in 10 cm of substrate, on raised green roof platforms in 10 cm of substrate, and in-ground were evaluated over three growing seasons (2009-11) to determine the practicality of using an extensive green roof system for food production. Tomatoes (*Lycopersicon esculentum*), green beans (*Phaseolus vulgaris*), cucumbers (*Cucumis sativus*), peppers (*Capsicum annuum*), basil (*Ocimum basilicum)* and chives (*Allium schoenoprasum*) were studied because of their common use in home gardens. All plants survived and produced biomass on the green roof, on green roof platforms and in-ground. All vegetable species yielded crops large enough for statistical analysis except for pepper in 2009 and 2010. Overall, yields were higher and of better quality in-ground during 2009 when plots were irrigated, and there were similarities in yields between the green roof and roof platforms. Variability in success of the vegetables was due in part to annual variation in weather conditions with weather having the greatest impact on cucumber. Biomass of basil was the same in the roof and platform plots two out of three years and was higher in the ground only during the first year when the ground plots were irrigated. After one year of growth there was no difference in chive yield among growing systems. Results suggest that with proper management, vegetable and herb production in an extensive green roof system is not only possible, but productive.

Introduction

In light of population growth trends (UNDESA, 2007; USCB, 2009**)** and concerns over food deserts in urban centers, malnutrition (van Averbeke, 2007; Peters et al., 2009; Windome et al. 2009) and the availability of land for agriculture (van Averbeke, 2007; Peters et al., 2009), alternatives to conventional agriculture need to be investigated. Urban agriculture, the production of agricultural products (vegetables, staple grains, dairy and meat) within the boundaries of an urban center, has received a great deal of interest (Enete and Achike, 2008; Graefe et al., 2009; Vagneron, 2007). Urban agriculture varies greatly in scale and amount of investment, in part due to the resources available to urban farmers (van Averbeke, 2007; Enete and Achike, 2008; Graefe et al., 2009; Nugent, 2002; Vagneron, 2007). Geography and climate also impact the forms of urban agriculture practiced (Enete and Achike, 2008; Nugent, 2002; Vagneron, 2007; de Zeeuw et al., 1999).

One of the biggest challenges facing urban agriculture is the availability of land (Nugent, 2002; de Zeeuw et al., 1999). There are numerous competing uses of land in urban centers including building development, which is highly profitable to land owners (Graefe et al., 2009; Nugent, 2002; Vagneron, 2007). Urban agriculture is generally not profitable to land owners, as farmers infrequently have formal use arrangements with land owners (Nugent, 2002; Thornton, 2009; de Zeeuw et al., 1999). Even when use agreements do exist, there can be conflict between the land owners and urban farmers because the development and use goals of the land owners may change (van Averbeke, 2007). This competition often forces urban farmers onto marginal vacant lots and brownfields. These lands are often found in industrial areas and may be contaminated by heavy metals, which results in contaminated food, and in turn creates a health hazard (Agbenin et al., 2009; Hu and Ding, 2009; Zhuang et al., 2009). If urban agriculture is to be a viable solution to increasing urban food issues, the conundrum of land availability and safety must be addressed.

In Germany, a country regarded as a leader in green roof technology, only 14 % of flat roofs are green (Kohler and Keeley, 2005). This leaves the remaining 86 % of flat roofs as a space resource with potential for productive use, which could enable the consumption of locally grown fresh produce by urban populations. The available space is even higher in the U.S., which lags Germany in green roof development. Some other possible benefits of utilizing green roof space to produce food include improved economic and food security, formalization of use rights, increased oversight of the use of agrichemicals and other fertilizers, and improved food safety (Whittinghill and Rowe, 2011). Although vegetables and herbs are now being grown on some green roofs (Arpels et al., 2005; Loder and Peck, 2004), there is currently very little information in the literature on how roof-top gardening (or growing conditions) affects vegetable yields and quality. Such information is necessary when examining the potential use of green roof space for larger scale vegetable production. It would also provide information useful in designing management programs to maximize both the quality and quantity of vegetables produced.

A wide variety of agricultural products have been produced in limited quantities on green roofs worldwide. These typically include many different herb species, peppers (hot and sweet)(*Capsicum anuum*), tomatoes (*Licopersicum esculentum*), carrots (*Daucus carota*), fennel (*Foeniculum vulgare*), beets (*Beta vulgaris*), beans (*Phasiolus vulgaris)*, peas (*Pisum sativum*), pumpkin (*Cucurbita spp*), zucchini (*Cucurbita pepo*), squash (*Cucurbuta spp*),, eggplant (*Solanum melongena*), turnip (*Brassica rapa*), broccoli (*Brassica oleracea*), ground cherries (*Physalis spp*), sweet potato (*Ipomoea batatas*), artichoke (*Cynara cardunculus*), and radish (*Raphanus sativus*) as well as other greens, berries, and melons (GRC, 2011). In some cases tree fruits such as cherry (*Prunus spp*), pear (*Prunus spp*), apple (*Malus spp*) (GRC, 2011), mushrooms, and rice are grown (Arpels, et al., 2005). Many green roof agricultural products are produced on intensive green roof systems in substrate depths greater than 15 cm (Coffman and Martin, 2004; GRC, 2011). These are typically 17.8 to 45.7 cm (7 to 18 in) deep (GRC, 2011) and the corresponding weight of 146 kg/m^2 (30 lb/ft^2) is heavier than most existing flat roofs can support (Dillion, 2010). This brings into question the scale at which green roof agriculture could be employed, unless adequate crop production can be achieved using less substrate.

The objective of this study was to evaluate the survival and productivity of vegetable and herb production in an extensive green roof system. Six vegetable and herb species were selected based on their common use in home gardens and their growth patterns. Each species was evaluated over three growing seasons for crop yield, crop quality, and biomass production on a rooftop and, green roof platforms in typical green roof substrate, and in-ground in natural soil. We hypothesized that there would be differences between the quantity and quality of produce among the three growing systems. Crops that perform poorly in the extensive green roof and green roof platforms are unlikely to be good candidates for urban agricultural production using green roof technology. Comparison of crop performance in the two green roof systems with production in-ground was used as an indicator for the suitability of extensive green roof agriculture as an alternative to urban agriculture in-ground.

Methods

Plot Locations and Preparation. Four vegetable and two herb cultivars were planted in four replicate plots in each of three growing systems: on a green roof, on green roof platforms, and in-ground. These growing systems were compared over three growing seasons, 2009, 2010, and 2011. Green roof plots were located on the Michigan State University (MSU) Plant and Soil Sciences Building (PSSB) in East Lansing, MI. Roof platform and ground plots were located at the MSU Horticultural Teaching and Research Center (HTRC) in Holt, MI, 6.3 km (4 mi) from the PSSB. The ground plots were located in Copac loam (USDA, 2012). The green roof and green roof platforms both contained 10.5 cm of green roof substrate laid over a XeroFlor XF-105 drainage mat (XeroFlor America, Durham, NC). Substrate consisted of 25% each of Haydite A and Haydite B heat-expanded shale, 35% 2NS sand, and 15% leaf compost (Renewed Earth, Kalamazoo, MI) and was installed May 29, 2009 and June 10, 2009, respectively. The depth of 10.5 cm was selected due to load capacity limitations of the PSSB roof. Green roof platforms were constructed according to VanWoert et al. (2005) and each 2.4 x 2.4 m platform was divided into three 0.8 x 2.4 m sections. In order to control for edge effect, vegetable plots were alternated between the three sections in the four replicate platforms. Plots on the PSSB measured 2.3 m x 1.4 m. Ground level plots were prepared by first treating them with glyphosate (Roundup®, Monsanto, St. Louis, MO). Once the existing vegetation was dead the area was deep tilled by spading on May 25, 2009. Four 0.8 x 2.4 m plots were created from the prepared area to simulate plots on the green roof platforms. Weather data was compiled from the Michigan Automated Weather Network (MAWN) station East Lansing/MSUHORT located at the HTRC adjacent to the platforms and ground plots.

Plant Selection and Maintenance. Vegetables and herbs selected were Roma (VF) tomatoes (*Lycopersicon esculentum*), early contender bush beans (*Phaseolus vulgaris*), bush pickle hybrid cucumbers (*Cucumis sativus*), Sweetheart® hybrid sweet peppers (*Capsicum annuum*) in 2009 and 2010, large-leaf Italian basil (*Ocimum basilicum*), chives (*Allium schoenoprasum*) (Gurney's Seed and Nursery Co., Greendale, IN), and Budapest hot banana

Table 2.1. Planting and maintenance dates for vegetable production during the 2009-11 growing seasons on the green roof, green roof platforms and in-ground.

Activity	**2009**	**2010**	**2011**
Seeds sown	May 9	May 3 and 14	May 6
Plugs planted:			
Green roof	May 26	May 15	June 18
Green roof platforms	May 29	May 15	June 16
In-ground	May 29	May 27	June 19
Pepper plugs planted:			
Green roof	May 26	July 1	July 6
Green roof platforms	May 29	May 29	June 30
In-ground	May 29	May 29	July 6
Irrigation started	May 29	June 30	June 7
Irrigation ended	October 2	October 3	October 1
Fertilizer application 1			
Green roof	May 30	July 1	July 22
Green roof platforms	June 13	July 1	July 22
In-ground	June 13	July 1	July 22
Fertilizer application 2			
Green roof	N/A	August 9	September 2
Green roof platforms	N/A	August 9	August 26
In-ground	N/A	August 12	August 26
Biomass harvest:			
Tomato	October 1 and 2	October 2 and 3	October 1 and 2
Bean	October 1 and 2	September 20	August 29
Cucumber	October 1 and 2	August 24	August 29
Pepper	October 1 and 2	October 2	October 1 and 2
Basil	October 1 and 2	August 22- October 2	October 1 and 2
Chives	October 1 and 2	October 2	October 1 and 2

Tomatoes are Roma (VF) tomatoes (*Lycopersicon esculentum*), beans are early contender bush beans (*Phaseolus vulgaris*), cucumbers are bush pickle hybrid cucumbers (*Cucumis sativus*), peppers are Sweetheart® hybrid sweet peppers in 2009 and 2010 and Budapest hot banana peppers in 2011 (*Capsicum annuum*), basil is large-leaf Italian basil (*Ocimum basilicum*), and chives (*Allium schoenoprasum*)

peppers (*C. annuum*) (Seedway, Hall, NY) in 2011. They were selected because of their availability, growth habit (determinate or bush variety), and common use in home gardens. Vegetables and herbs were sown from seed into 48-cell plug trays in early May of each year (Table 2.1) and grown outdoors, in East Lansing, MI. Budapest hot banana peppers were planted from seed into 98-cell plug trays on April 6, 2011 and grown in a greenhouse until May 24, 2011, then transferred to a lath house at the HTRC.

Due to the limited space available two plants of each type were planted from plugs into the green roof, green roof platform, and ground plots (Table 2.1). Plants within each plot were evenly spaced in two rows of six. The specific location of each plant was selected randomly in 2009. Plant locations remained the same for each of the three growing seasons because of the perennial nature of chives. Plots on the PSSB roof were watered three times daily for 20 min using a sprinkler throughout the growing season of 2009, and using micro-emitters throughout the growing seasons of 2010 and 2011 (Table 2.1). Throughout the 2009 growing season platforms were watered three times daily for 20 min using overhead sprinklers and three times daily for 5 min using micro-emitters throughout the 2010 and 2011 growing seasons (Table 2.1). Ground plots were watered daily with overhead sprinklers during establishment, then as needed for the 2009 growing season only. A comparison of production in each growing system using minimal management was the goal of this study so irrigation was stopped in-ground after 2009, because scheduled irrigation of back-yard gardens with clay soils in Michigan is not usually necessary. Occasional manual irrigation was provided to the ground plots during periods of drought in 2010 and 2011. Irrigation in the platforms was however necessary to maintain survival of the vegetable plants because herbaceous plants do not survive well in shallow green roof substrate without irrigation (Monterusso et al., 2005). Lesco Professional Landscape and Ornamental All-Purpose Fertilizer 14-14-14 (Lesco, Inc., Cleveland, OH) (Table 2.2) was applied to all plots at a rate of 25 g/m^2 once in 2009, and twice in 2010 and 2011 (Table 2.1).

Table 2.2. Composition of Lesco Professional Landscape and Ornamental All-Purpose Fertilizer 14-14-14 (Lesco, Inc., Cleveland, OH).

Nutrient	**Percent Content by Weight (%)**
Total Nitrogen	14.00
Ammoniacal Nitrogen	5.48
Urea Nitrogen	8.55
Phosphate (P_2O_5)	14.00
Soluble Potash (K_2O)	14.00
Total Sulfur	19.40
Free Sulfur	14.40
Combined Sulfur	5.00
Total Iron	0.45
Water soluble Iron	0.005
Total Manganese	0.45
Water soluble manganese	0.05
Chlorine Max	2.00

Data collection and Analysis. Tomatoes, beans, cucumbers, and peppers were harvested as they ripened until just before the first frost when all remaining fruit were harvested, combined for each plot, and weighed. Sizes of individual vegetables were measured on the two longest axes using a caliper. Vegetables were divided in to size categories based on USDA standards (USDA, 1991; USDA, 1959; USDA 1936) and size categories were assigned numbers for analysis with 1 representing the smallest size category for each vegetable and 5, 6, and 4 representing the largest size category for tomatoes, beans and cucumbers, respectively. Tomato color was also determined based on USDA standards (USDA, 1991; USDA, 1959; USDA 1936) and the color category number (eg. 1 = green, 6 = red) was used for analysis. Potential acceptability of the vegetables to the consumer was rated according to USDA standards (USDA, 1991; USDA, 1959; USDA 1936; USDA, 2009). Reasons for unacceptability, such as insect or disease damage, discoloration, or scarring, were recorded. Quality ratings were used to determine crop quality according to USDA standards with lower numbers representing higher quality and 4 indicating a cull (USDA, 1991; USDA, 1959; USDA 1936; USDA, 2009). The number of fruit, total yield in grams and marketable yield in grams based of fruit quality were also recorded at the time of harvest. Marketable percent of the yield was calculated from total and marketable yield data.

After the first frost in 2009 and just before the first frost in 2010 and 2011, whole basil and chive plants were harvested at the soil or substrate surface (Table 2.1). In 2010, basil leaves were evaluated for marketability by removing all leaves and sorting based on the presence of insect damage, discoloration, sun scalding or disease. Basil and chive plant material was weighed fresh, dried at 60 ˚C for 1 wk and weighed again to determine biomass. At the end of each growing season, tomato, bean, cucumber and pepper plants were also cut even with the soil or substrate surface, and their biomass was determined (Table 2.1). Biomass dry weight was also measured but will not be discussed because it is correlated to biomass wet weight.

Data were analyzed using SAS (Version 9.1, SAS Institute, Cary, NC). Correlations were found between number of fruit and total yield, marketable yield and plant biomass (R^2 from 0.166 to > 0.8); total yield and marketable yield and plant biomass (R^2 from 0.233 to > 0.8); and marketable yield and plant biomass (R^2 from 0.1816 to 0.8288). Due to these high correlations results for fruit number, marketable yield and plant biomass will be presented in tables, but not discussed in the text. All data were checked for normality prior to analysis of variance. Non-normal data were analyzed after applying a logarithmic transformation for tomato number, total yield and marketable yield, bean number, total yield, and biomass wet weight, basil marketable yield, and chive fresh weight yield and a square root transformation for cucumber total weight. All values are presented as back-transformed data. Influence diagnostics were used to identify outliers, which were removed if they were deemed unrepresentative. Mean fruit size, fruit quality, total yield, marketable yield and biomass of each species were analyzed using an ANOVA model with growing system as a fixed effect. Significant differences among treatments were determined using multiple comparisons by LSD with an alpha of 0.05 (PROC MIXED, Version 9.1, SAS Institute). No comparisons among species were made.

Results

Weather. During 2009, maximum ambient air temperatures in May, July and August were lower than the following two growing seasons and similar maximum temperatures were recorded during 2010 and 2011 (Figure 2.1). Minimum ambient air temperatures were also lower in May, September, and October in 2009, than those recorded in 2010 and 2011. Total precipitation was greatest during 2011, however, 2009 experienced more precipitation during June and August than 2010 and 2011 but less in September and July (Figure 2.1). Incoming solar radiation was similar for all three growing seasons with totals for June, July, August and September of 2.24, 2.16, and 2.21 million kJ/m^2 for 2009, 2010, and 2011, respectively.

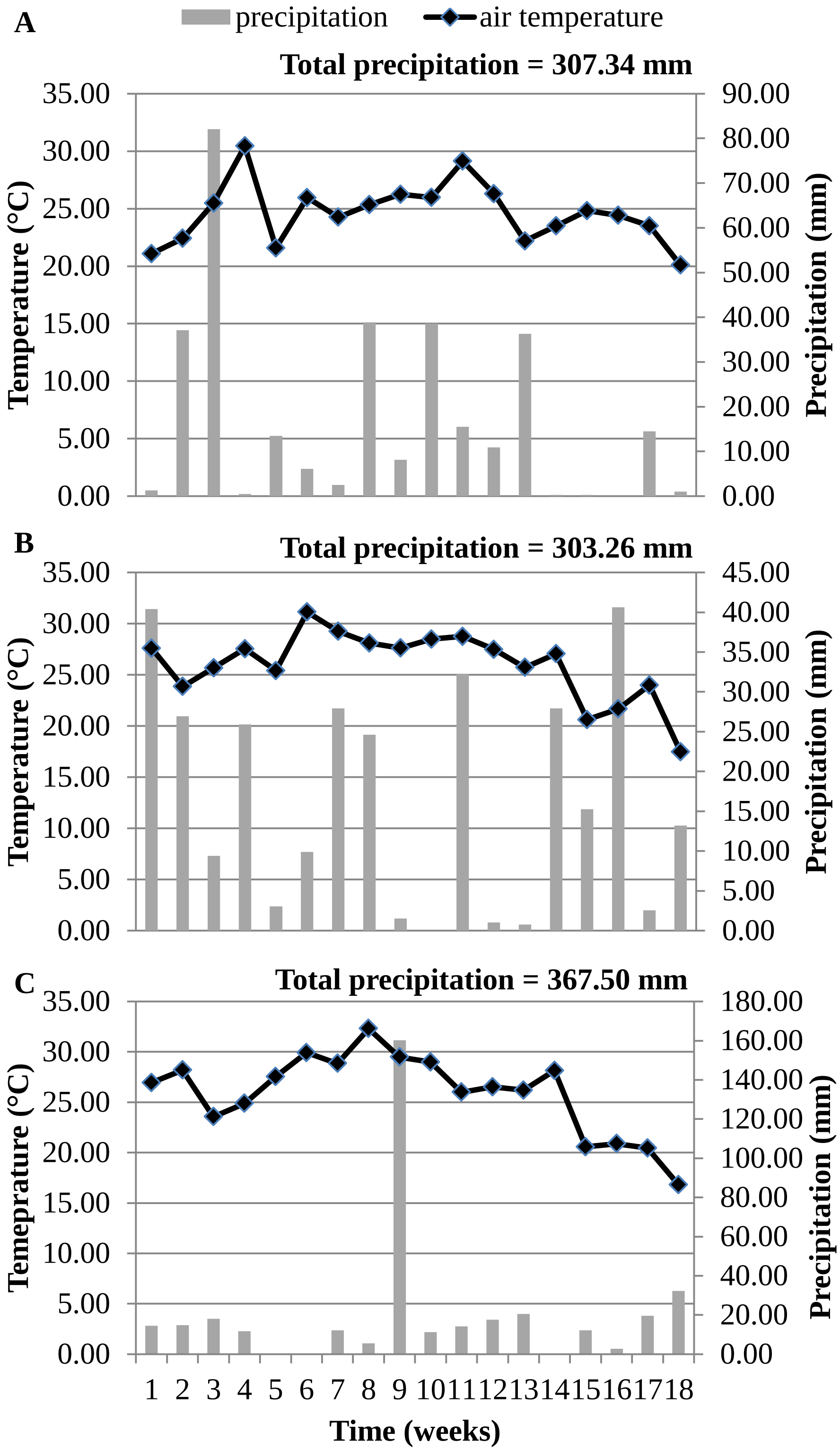

Figure 2.1. Weekly average maximum air temperature in Celsius and weekly total precipitation in mm for the growing seasons of (A) 2009 (May 31-Oct 2) (B) 2010 (May 25-Oct 2) and (C) 2011 (May 29-Oct 1).

Table 2.3. Harvest indicators for tomatoes (*Lycopersicon esculentum*) grown on the green roof, green roof platforms and in-ground during the 2009-11 growing seasons.

Variable	Growing System	2009	2010	2011
Fruit Size	**Green roof**	3.1 Ab	1.3 Bb	1.2 Ba
	Green roof platform	1.9 ABc	2.2 Aa	1.4 Ba
	In-ground	3.5 Aa	1.0 Bb	1.5 Ba
Fruit Color	**Green roof**	2.5 Aa	1.7 Bb	2.2 Ab
	Green roof platform	1.3 Bb	3.0 Aa	3.0 Aa
	In-ground	1.4 Bb	1.8 ABb	2.0 Ab
Fruit Grade	**Green roof**	2.0 Aa	3.4 Bb	2.1 Aa
	Green roof platform	2.9 Bb	2.7 Ba	1.8 Aa
	In-ground	2.9 Bb	3.4 Cb	2.1 Aa
Number of Fruit	**Green roof**	18.0 ABb	36.6 Aa	13.1 Bab
	Green roof platform	10.0 Bb	22.6 Aa	17.3 ABa
	In-ground	132.4 Aa	4.9 Bb	7.3 Bb
Total Yield (g)	**Green roof**	401.6 Ab	534.1 Aa	143.0 Ba
	Green roof platform	102.6 Bc	571.0 Aa	238.3 ABa
	In-ground	3273.4 Aa	57.1 Cb	147.2 Ba
Marketable Yield (g)	**Green roof**	401.6 Ab	281.3 ABa	136.0 Ba
	Green roof platform	87.3 Bc	458.5 Aa	235.2 Aa
	In-ground	1597.3 Aa	43.7 Cb	146.7 Ba
Marketable Percent of Yield (%)	**Green roof**	100.0 Aa	52.9 Bb	95.2 Aa
	Green roof platform	85.7 Aa	81.5 Aa	98.7 Aa
	In-ground	49.6 Bb	82.4 Aa	99.7 Aa
Biomass Wet Weight (g)	**Green Roof**	142.1 Bb	551.2 Aa	197.3 Ba
	Green roof platform	93.4 Bb	305.1 Ab	95.6 Ba
	In-ground	1280.3 Aa	188.5 Bb	246.6 Ba

Sizes, colors and grades based on USDA standards for fresh tomatoes (USDA, 1991). Marketable yield based on fresh weight of all fruit of a marketable grade according to USDA standards. Each mean represents four observations. Means were separated using LSD with an alpha of 0.05. Capital letters in rows indicate differences among years within growing systems and lower case letters in columns indicate differences among growing systems within years for each variable. Letters for number, total yield, and marketable yield data indicate significant difference in the transformed data.

Tomato. Results for all variables measured for tomato are listed in Table 2.3. The largest fruit were produced in –ground in 2009 and in platforms in 2010. In 2011, growing system did not affect fruit size. Fruit harvested from the roof and ground were larger in 2009 than in later growing seasons. Fruit color was closest to red at harvest on the roof in 2009 and on the platforms in 2010 and 2011. There was no consistent pattern of fruit color across years. The lowest grade fruit were produced on the roof in 2009 and the platforms in 2010. Growing system had no effect on fruit grade in 2011. Fruit grown in–ground and in platforms in 2011 graded lower than any other year.

In 2009, plants grown in-ground produced the highest total yield, but the lowest marketable percent of yield. A reversal of this was seen in 2010 when plants on the roof and platforms produced the highest total yield but plants on platforms and ground produced the highest marketable percent of yield. Growing system had no effect total yield or marketable percent of yield in 2011 and year had no effect on marketable percent of yield from the platforms.

Bean. Results for all variables measured for beans are listed in Table 2.4.Growing system had no effect on pod size in 2009 or 2010. Pods were smallest in 2011 for all three growing systems and lower in-ground than the roof and platform that year. Pods were of lowest grade in 2009, when growing system had no effect on pod grade. In 2010, plants on platforms produced the lowest grade pods and in 2011 plants on the roof produced the lowest grade pods.

In 2009, total yield was highest in-ground, but growing system had on effect on marketable percent of yield. Plants growing on platforms had higher total yield in 2010 than the other growing systems, but had lower marketable percent of yield. In 2011, the total yield from the platforms did not differ from either growing system and the marketable percent of yield did not differ from the ground but was higher than that of roof plants. Total yields were highest in 2009, 2010 and 2011 for the ground, platform and roof, respectively. Marketable percent of yield was highest in 2009.

Table 2.4. Harvest indicators for beans (*Phaseolus vulgaris*) grown in the green roof, green roof platforms and in-ground during the 2009-11 growing seasons.

Variable	Growing System	2009	2010	2011
Pod Size	**Green roof**	3.7 Aa	3.3 ABa	2.8 Ba
	Green roof platform	4.1 Aa	3.5 Aa	2.0 Ba
	In-ground	4.4 Aa	3.6 Ba	1.8 Cb
Pod Grade	**Green roof**	1.8 Aa	3.2 Cb	3.1 Ba
	Green roof platform	1.8 Aa	2.5 Ba	3.5 Cb
	In-ground	1.8 Aa	3.1 Bb	3.7 Bb
Number of Pods	**Green roof**	4.4* Bb	4.3 Bb	13.7 Aa
	Green roof platform	7.0 Bb	31.3* Aa	5.1* Ba
	In-ground	20.1 Aa	6.5 Bb	5.9 Ba
Total Yield (g)	**Green roof**	6.7* Bb	5.0 Bb	22.8 Aa
	Green roof platform	14.9 Bb	81.2* Aa	12.9 Bab
	In-ground	81.1 Aa	12.6 Bb	3.7 Bb
Marketable Yield (g)	**Green roof**	1.8* Aa	3.2 Ca	3.1 Bb
	Green roof platform	1.8 Aa	2.5 Bb*	3.5 Ca
	In-ground	1.8 Aa	3.1 Ba	3.7 Ba
Marketable Percent of Yield (%)	**Green roof**	93.3* Aa	38.7 Ca	22.6 Bb
	Green roof platform	87.1 Aa	68.6 Bb*	73.7 Ca
	In-ground	84.7 Aa	55.6 Ba	48.0 Ba
Biomass Wet Weight (g)	**Green roof**	4.7 Ab	3.4 Ab	12.7 Aa
	Green roof platform	11.0 Bb	47.5 Aa	13.4 Ba
	In-ground	54.3 Aa	8.3 Bb	6.5 Ba

***** Based on 3 observations due to the exclusion of outliers.
Sizes, and grades based on USDA standards for snap beans for processing (USDA, 1959). Marketable yield based on fresh weight of all fruit of a marketable grade according to USDA standards. Each mean represents four observations. Means were separated using LSD with an alpha of 0.05. Capital letters in rows indicate differences among years within growing systems and lower case letters in columns indicate differences among growing systems within years for each variable. Letters for number, total yield, and biomass data indicate significant difference in the transformed data.

Cucumber. Results for all variables measured for cucumber are listed in Table 2.5.There was no clear pattern of variation in fruit size among years. During 2009 fruit harvested from the platforms were smaller than those harvested from the other growing systems and during 2010 fruit harvested in-ground were smaller. Growing system had no effect on fruit size in 2011 or fruit grade in 2010 and year had no effect on grade of fruit harvested from the roof or platforms.

During 2011, fruit harvested from the roof were of lower grade than those harvested from any other growing system that year.

Table 2.5. Harvest indicators for cucumbers (*Cucumis sativus*) grown in the green roof, green roof platforms and in-ground during the 2009-11 growing seasons.

Variable	**Growing System**	**2009**	**2010**	**2011**
Fruit Size	**Green roof**	2.3 ABa	2.9 Aa	1.6 Ba
	Green roof platform	1.0 Bb	2.6 Aa	2.0 ABa
	In-ground	2.8 Aa	1.3 Bb	2.0 ABa
Fruit Grade	**Green roof**	3.2 Aab	3.7 Aa	3.1 Aa
	Green roof platform	4.0 Ab	3.5 Aa	4.0 Ab
	In-ground	3.0 Aa	4.0 Ba	3.5 ABb
Number of Fruit	**Green roof**	1.5 Bb	3.0 Aa	0.5 Bb
	Green roof platform	0.7 Bb	4.2 Aa	2.0 Ba
	In-ground	4.2 Aa	0.7 Bb	3.2 Aa
Total Yield (g)	**Green roof**	56.2 Bb	380.4 Aa	14.9 Bb
	Green roof platform	8.0 Cc	426.1 Aa	139.4 Ba
	In-ground	403.7 Aa	13.5 Cb	227.9 Ba
Marketable Yield (g)	**Green roof**	52.2 ABb	120.9 Aa	28.8 Bab
	Green roof platform	0.0 Bb	109.9 Aa	100.9 Aa
	In-ground	362.1 Aa	0.0 Bb	0.0 Bb
Marketable Percent of Yield (%)	**Green roof**	44.4 Ab	29.2 Aa	25.0 Ab
	Green roof platform	0.0 Bc	25.2 Ba	70.2 Aa
	In-ground	90.4 Aa	0.0 Bb	0.0 Bb
Biomass Wet Weight (g)	**Green roof**	10.7 Bb	75.9 Aa	18.4 Ba
	Green roof platform	13.5 Bb	34.1 Ab	22.8 ABa
	In-ground	45.7 Aa	7.5 Bc	19.6 Ba

Sizes and grades based on the USDA standards for pickling cucumbers (USDA, 1936). Marketable yield based on fresh weight of all fruit of a marketable grade according to USDA standards. Each mean represents four observations. Means were separated using LSD with an alpha of 0.05. Capital letters in rows indicate differences among years within growing systems and lower case letters in columns indicate differences among growing systems within years for each variable. Letters for total yield data indicate significant difference in the transformed data.

Total yields and marketable percent of yield exhibited similar patterns in 2009, with the ground performing best and in 2010, with the roof and platforms performing better than in-ground plants. In 2011, there was no difference between the total yield of platform and in-ground plants and marketable percent of yield was highest in the platforms. Plants grown on the roof and platforms had higher total yields in 2010 than any other year. Year had no effect on marketable percent of yield of roof plants. Marketable percent of yield of the platforms was highest in 2011 and the total yield and marketable percent of yield of in-ground plants was highest in 2009.

Pepper. Yields from sweet peppers in 2009 and 2010 were extremely limited (data not shown). Statistical analysis was not performed because we believe that this lack of success was the result of cultivar choice and not the experimental treatments. Results for all variables measured for Budapest hot banana pepper are listed in Table 2.6. The size of peppers harvested from the roof did not differ from any growing system in 2011. Growing system had no effect on grade of fruit in 2011. Total yields of roof and platforms plants were higher than that from the ground. Marketable percent of was higher from the roof than either of the other growing systems.

Table 2.6. Harvest indicators for Budapest hot banana peppers (*Capsicum annuum*) grown in the green roof, green roof platforms and in-ground during 2011 growing season.

Variable	Green roof	Green roof platform	In-ground
Fruit Diameter (cm)	2.0 ab	2.53 a	1.1* b
Fruit Grade	2.7 a	2.7 a	4.0* a
Number of Fruit	3.0 a	3.0 a	0.5 b
Total Yield (g)	25.2 a	31.0 a	0.2 b
Marketable Yield (g)	23.1 a	20.8 a	0 b
Marketable Percent of Yield (%)	72.2 a	18.8 b	0 b
Biomass Wet Weight (g)	15.1 a	26.0 a	14.6 a

* Mean based on only two observations

Sizes and grades based on USDA standards for sweet peppers (USDA, 2005). Marketable yield based on fresh weight of all fruit of a marketable grade according to the USDA standards. Each mean represents four observations. Means were separated using LSD with an alpha of 0.05. Letters in rows indicate differences among growing systems for each variable.

Basil. Basil biomass fresh weight was higher in-ground in 2009, in platforms in 2010 and lower in-ground in 2011 (Table 2.7). Biomass fresh weight in 2009 was greater than any other year for in-ground plants (Table 2.7). Marketable yield of basil was lower on the roof (Table 2.8) and the marketable percent of biomass was higher in-ground (Table 2.8).

Table 2.7. Biomass fresh weight (g) of basil (*Ocimum basilicum*) for the 2009-11 growing seasons on the green roof, green roof platforms and in-ground.

Growing System	2009	2010	2011
Green roof	133.3 Bb	266.1 ABb	467.3 Aa
Green roof platform	62.7 Bb	605.1 Aa	694.7 Aa
In-ground	458.4 Aa	227.5 Bb	205.6 Bb

Each mean represents four observations. Means were separated using LSD with an alpha of 0.05. Capital letters denote differences among years within growing systems; lower case letters denote differences among growing systems within years.

Table 2.8. Marketable fresh weight yield (g) and marketable percent of biomass of basil (*Ocimum basilicum*) for the 2010 growing season on the green roof, green roof platforms and in-ground.

Growing System	Marketable yield (g)	Percent of marketable biomass
Green roof	0.2 b	0.8 b
Green roof platform	3.7 a	6.8 b
In-ground	4.0 a	27.8 a

Each mean represents four observations. Means were separated using LSD with an alpha of 0.05. Letters denote differences among growing systems. Differences among growing systems for marketable yield are for transformed data.

Table 2.9. Fresh weight yields (g) of chives (*Allium schoenoprasm*) for the 2009-11 growing seasons on the green roof, green roof platforms and in-ground.

Growing System	2009	2010	2011
Green roof	1.1 Bc	272.1 Aa	638.3 Aa
Green roof platform	25.0 Ba	439.1 Aa	601.7 Aa
In-ground	5.2 Bb	239.3 Aa	475.3 Aa

Each mean represents four observations. Means were separated using LSD with an alpha of 0.05. Capital letters denote differences among years within growing systems and lower case letters denote differences among growing systems within years for transformed data.

Chives. At the end of the 2009 growing season, platform plants had a higher fresh weight yield than roof or in-ground plants (Table 2.9). Growing system had no effect on fresh weight yield in 2010 or 2011. Fresh weight yields were lower in 2009 with no difference between 2010 and 2011 (Table 2.9).

Discussion

In 2009, tomato, bean, cucumber and basil plants grew better in-ground than either of the green roof systems with a few exceptions. This was most likely due to the irrigation that was supplied to the ground plots in 2009 but not 2010 or 2011. Supplemental irrigation enabled larger fruit, a greater number of fruit, and more biomass than the other growing systems that year and greater than the other years in that growing system. The exceptions include fruit color and grade and marketable percent of yield of tomato (Table 2.3), fruit size and grade, marketable yield and percent of marketable yield of bean (Table 2.4), and fruit grade of cucumber (Table 2.5). Although rooftop temperatures were not measured in this study, a previous study using the PSSB roof compared measured green and ballast roof temperatures to those at ground level from the MAWN weather station used in this study (Getter et al, 2011). The authors found that temperatures on the green roof were warmer than nearby ground-level temperatures throughout the course of their study. This combined with fewer observed pests on the roof likely resulted in the higher number of ripe fruit and higher quality tomato fruit in that growing system (Table 2.3). For beans, the only measured variables that did not show plants from in-ground plots outperforming the roof and platform plants showed no effect of growing system (Table 2.4). There was also no difference between the fruit grade of cucumber from in-ground and roof level plots (Table 2.5).

When comparing all three growing seasons there was no consistent pattern for all of the vegetable and herb species examined. Bean was the only species to perform better in 2009 than either of the two following growing seasons (Table 2.4). This may have been because of the larger amount of precipitation early in the season and shorter periods of time without rain than the other two growing seasons. Lower temperatures in July when there was less rain may have also contributed to this success. There was no clear difference in performance in 2010 and 2011 for either tomato (Table 2.3) or basil (Table 2.6). Although 2011 was warmer, both years were within the range of temperatures required for tomato production and the irrigation supplied in 2011 adequately made up for rain during the dry periods in June and August. The same may be true of basil. Drastic difference between the results of cucumber from 2010 and 2011, suggests that it was more susceptible to the long periods of warm dry weather that took place in 2011, affecting performance in all growing systems. It should be noted that although fruit grades for cucumber were high for all three growing season in all growing systems, this was at least in part due to size restrictions in the USDA grades (USDA, 1936). USDA grade 3 cucumbers (the lowest grade before cull (grade 4) has a listed maximum length of 15.2 cm (6 in) and maximum diameter of 5.7 cm (2.25 in) (USDA, 1936) and many fruit harvested grew to lengths or diameters greater than these restrictions but did not show flaws that would warrant culling. Although the fruit grade of Budapest hot banana pepper was not very high (Table 2.6), we noted some bitterness flavor in the fruit. This could influence consumer appeal and further research could determine the cause and suggest a remedy. Chive, the only perennial species, exhibited its lowest yields in 2009 (Table 2.9), the first year of the growth for this perennial species. This suggests that it may be beneficial to wait for the second growing season to harvest. Recommendations for harvesting chives state that harvesting every 4 to 6 wks throughout the growing season stimulates multiplication (Swaider and Ware, 2002), which would result in greater yields that a single harvest at the end of each growing season. This may however require prohibitive labor inputs if implemented on rooftops on a larger scale than set harvests that correspond with other crop harvest dates.

After the 2009 growing season, there were fewer clear differences in the performance of vegetable and herb species among the three growing systems. Many similarities in performance of vegetables in green roof and green roof platforms suggest that green roof platforms are and adequate proxy for actual roof tops for experimentation. Performance of all vegetable and herb species with the exception of sweet pepper on the roof and platforms was as good as if not better than their performance in-ground. It should, however be noted that this coincides with the discontinuation of irrigation for the in-ground plots. Sweet pepper had poor germination in 2010, and yielded few fruit in either 2009 or 2010. This resulted in the removal of this variety from the study and suggests that it may not be well suited to production in an extensive green roof system. Results suggest that tomato, bean, cucumber, Budapest hot banana pepper, basil and chive are good candidates for production in an extensive green roof system. *Allium* species have been considered good candidates for growth on green roofs for some time.

A comparison of yields form this study and those estimated based on United States production area and yields for 2011 is also instructive. First it should be noted that the overall planting density in this study, 6.35 plants/m^2, is higher than those calculated from recommended plant and row spacing for tomatoes and peppers (2.4 to 4.34 and 3.25 to 4.10 plants/ m^2, respectively), at the high end of normal for cucumbers (1.74 to 6.6 plants/ m^2) and low for beans (25.06 to 38.65 plants/ m^2) (Swiader and Ware, 2002). Reported yields for tomato, bean, cucumber and hot pepper are 3,233, 574, 1,857, and 2,316 g/m^2, respectively (USDA, 2011). In order to make those yields comparable with the yields reported here, yield per plant was estimated to account for differing planting densities. The highest yields achieved in this study were lower than those estimated from USDA reports with the exception of tomatoes and beans

(Table 2.10). The highest yields for tomato and beans were however much higher than any other yields for those vegetables and occurred in the in-ground plots in 2009 when irrigation was supplied to those plots. The next highest yields, from the green roof platforms in 2010, were lower than those estimated from USDA reports (Table 2.10). This could be an indication of water needs not being met. The issue of low yields, and problems with successfully producing quality, good looking and tasting fruit from pepper cultivars could be resolved through different management practices.

Table 2.10. Estimated yield in grams per plant for the highest yields achieved in this study and from reported growing area and yield data reported by the USDA (2011) and recommended planting densities based on row and plant spacing (Swiader and Ware, 2002).

Vegetable	**Estimated from this study**		**Estimated yield (g/plant) from USDA (2011) and Swaider and Ware (2002)**
	Growing System and Year	**Yield (g/plant)**	
Tomato	In-ground, 2009	1636.7	
	Green roof platform, 2010	285.5	744.93-1347.08
Bean	In-ground, 2009	40.55	
	Green roof platform, 2010	40.6	14.85-22.90
	Green roof, 2011	11.4	
Cucumber	Green roof platform, 2010	213.05	281.36-1067.24
Pepper	Green roof platform, 2011	15.49	712.62-564.88

Estimated yields from this study derived by dividing the indicated mean by 2 plants. USDA (2011) yield estimates derived by dividing the USDA reported yield/m^2 by estimated plant densities derived from Swiader and Ware (2002).

Conclusions

Although we expected that there would be differences between production on the green roof, green roof platform and in- ground based on differences between the green roof and green roof platform and in-ground growing conditions, this was generally not the case. Yearly variation in weather seemed to have a larger impact on some of the species examined, especially when irrigation and fertilizer were used to manage issues of substrate moisture and nutrient availability in the green roof substrate. This study has shown that it is possible to produce tomato, bean, cucumber, pepper, basil, and chive in an extensive green roof on a small scale in Michigan with irrigation and minimal fertilizer inputs. A more sophisticated management strategy could enable production of yields similar to those produce in-ground in the United States. This study represents a potentially significant starting point in the literature of green roof agriculture, which is currently limited. More research on irrigation efficiency, nutrient management, pest and pollinator management and cultivar choice are needed. Not only to expand the species and cultivars that are known to do well on extensive green roofs, but to make their production more efficient, and to understand and minimize negative impacts on the benefits already provided by green roofs, such as stormwater retention, energy savings and mitigation of the urban heat island (Getter and Rowe, 2006).

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CHAPTER THREE:

Evaluation of nutrient management and mulching strategies for vegetable production on an extensive green roof

Abstract

Substrate nutrient and moisture management are two major concerns in green roof agriculture. These concerns are amplified when using extensive green roof systems for food production. Currently no recommendations or best management practices exist to guide rooftop farmers in dealing with these issues. The purpose of this study was to explore three mulching strategies (no mulch, pine bark mulch, and a living *Sedum* mulch) and three fertilization regimens (25, 50, and 100 g/m^2 of a 14-14-14 N-P-K slow release fertilizer applied twice during each growing season) over two growing seasons to determine their possible benefits to rooftop vegetable and herb production. Tomatoes (*Lycopersicon esculentum*), beans (*Phaseolus vulgaris*), cucumbers (*Cucumis sativus*), sweet peppers (*Capsicum annuum*), basil (*Ocimum basilicum*), and chives (*Allium schoenoprasum*) were included in this study because of their common use in home gardens. Crops performed better in 2010 than 2011 because of more extreme temperature and precipitation variations during 2011. When there were differences among mulch treatments, pine bark mulch treatment usually resulted in higher productivity than the live *Sedum* mulch. Mixed effects of live *Sedum* mulch on crop production are consistent with other literature on the use of living mulches in vegetable production. Among fertilizer treatments, 100 g/m^2 treatment outperformed lower rates in most cases. Instances of higher performance of the other fertilizer treatments are likely because those treatments adequately supplied the crops with phosphorus and potassium. Further research into more types of mulch and the effect those mulches have on the green roof microclimate could provide a better understanding of the role that mulching could play in green roof agriculture. More research into different types of fertilizers with different compositions could also help in the development of an efficient and productive nutrient management practice.

Introduction

Substrate fertility and vegetation water needs are two major concerns on both green roofs and in agriculture. Fertility and nutrient management are issues on green roofs because most green roof substrates are engineered with less than 20% organic matter, which is usually combined with coarse heat expanded materials such as slate or shale. This and the remaining components of green roof substrates have high permeability and low cation exchange capacity (Emilsson et al., 2007). Substrate organic matter breaks down over time (Emilsson, 2004; Hathaway et al., 2008) and must either be replaced to maintain substrate depth, which could be a cumbersome process on a rooftop, or managed with ferilizers, especially for plants with high nutrient demands such as most vegetables. Both the breakdown of organic matter and the use of fertilizers have been shown to lead to nutrient leaching (Czemiel Berndtsson, 2010; Emilsson, 2004; Hathaway et al., 2008).

Examination of the literature on green roof water quality reveal mixed results on the extent to which nitrogen (N) is increased in runoff (Rowe, 2011). Czemiel Berndtsson et al (2006) examined runoff from several green roofs in southern Sweden and found that some experienced reduced nutrient loading compared to control roofs, while others showed increased nutrient loading. Hathaway et al. (2008) and MacMillan (2004) observed higher runoff nutrient loading from green roofs than from their respective control roofs. There is however a reduction in runoff nutrient content with increasing roof age and decreasing losses of nutrients such as phosphorus (P) from the green roof substrate (Czemiel Berndtsson, 2010). The addition of fertilizers also results in nutrient leaching into runoff water, especially if those fertilizers are highly water soluble (Czemiel Berndtsson, 2010; Emilsson, 2004; Emilsson et al., 2007). The use of municipal water supply (MacMillan, 2004) and amendments such as biochar (Beck et al., 2011), can increase or decrease runoff nutrient loading, respectively. This stresses the importance of initial nutrient content of the substrate and subsequent fertilization and irrigation practices on runoff quality.

A balance between meeting the nutritional needs of the vegetation and adversely impacting the quality of runoff from the roof must be met. This balance may be particularly difficult to achieve when considering vegetable production on green roofs and it is the major environmental concern of rooftop gardening (Whittinghill and Rowe, 2011). The fertilizer recommendation for typical extensive green roofs is 5 g N/m^2 (FLL, 1995). Nitrogen recommendations for agricultural vegetable crops grown in soil range from 4.5 g/m^2 for snap beans and peas to 22.4 g/m^2 for celery (Warncke et al., 2004). These are much higher values than those recommended for typical green roofs, but could still be low estimates for N needs for roof top vegetable production because of the differences between soil and green roof substrate. Whittinghill (2012) showed that it was possible to produce vegetables on an extensive green roof with a minimal fertilizer input of 25 g/m^2 of a 14-14-14 N-P-K slow release fertilizer, however yields were much lower than those expected based on ground level soil production in the United States. Yield improvements are possible with larger quantities of nutrient amendments, but there is the potential for increasing nutrient concentrations in runoff water. One method of achieving this balance between plant nutrient needs and runoff quality would be to use the lowest quantity of fertilizer input possible while still achieving acceptable production results. With the use of slow release fertilizers this would increase the probability that more of the fertilizer can be taken up by plants before it is leached from the substrate (Emilsson et al., 2007).

A second practice to reduce nutrient leaching into runoff water is simply to limit runoff. This could be achieved by utilizing substrate moisture management practices to reduce the amount of irrigation that is applied to the production roof. Mulching is a common method of managing soil moisture content and plant water needs in agriculture (Ham, et al., 1993; Masiunas et al., 2003; Ngouajio and Ernest, 2001, Tanner, 1974; Tarara, 2000). Mulch has been shown to affect the energy balance in the field, by reducing evaporation through the substrate surface and by altering surface and near surface temperatures (Gruda, 2008; Law et al., 2006; Monks et al., 1997; Olsen and Gounder, 2001; Warnick et al., 2006). A variety of plastic and organic mulches can be used to achieve these effects. Some organic mulches, such as wood fiber, can however lead to N immobilization because of their high carbon to N ratio and adversely affect fruit yields (Gruda, 2008). Mulching may also enhance the ability of a green roof to support vegetable and herb plants while minimizing the necessity of irrigation. On unmulched extensive green roofs, many herbaceous native plants exhibit poor survival and health without irrigation (Monterusso et al., 2005), which makes managing irrigation and irrigation efficiency on vegetable producing green roofs important for production.

A third option which addresses nutrient runoff would be to collect runoff and recycle on the roof, thus developing a closed system. However, there are issues regarding the buildup of salts in the irrigation water and substrate. Therefore, the recycling option is not considered in this study.

The use of live vegetative cover is also a practice which impacts the energy balance, and therefore water loss from an agricultural setting. Its effects can, however, vary depending on the plant used and the crop being produced (Abdul-Baki and Teasdale 1993) and can either be positive (Abdul-Baki et al., 1996; Abdule-Baki and Teasedale, 1993) or negative due to competition with the crop plants (Roberts and Anderson, 1994). The use of live plants as a mulch had been explored on green roofs. Butler and Orians (2011) suggested that the use of *Sedum album* as nurse plants for more sensitive herbaceous plants could improve survival and appearance of those plants. This suggestion was based on previous studies showing that *Sedum* reduced evaporative water loss from the substrate (Durhman et al., 2006; Wolf and Lundholm, 2008). It has also been established that green roof substrate covered by plants, regardless of species, contains more moisture than uncovered substrate (VanWoert et al., 2005). Butler and Orians (2011) found that the use of a living *Sedum* mulch reduced substrate temperatures and improved herbaceous plant health during periods of drought. During periods where water was not limiting however, the *Sedum* acted as a competitor with the herbaceous plants. It is possible that such a mulching strategy could be beneficial in green roof agriculture.

The two main objectives of this study were to develop a mulching strategy and a fertilization regimen that would improve crop production in extensive green roof agriculture. Two types of mulch, pine bark and live *Sedum* mulch, and a no mulch control were examined. It was hypothesized that the two mulches would reduce evaporation from the substrate surface and improve plant productivity. A secondary goal of this study was the evaluation of *Sedum* as a viable living mulch solution for vegetable or herb production on green roofs. Three fertilization treatments were examined to determine if a low rate of fertilizer application can produce quality crops and reduce potential impacts on runoff water quality.

Table 3.1. Initial physical and chemical properties of green roof substrate.

Component	Unit
Total Sand (%)	86
Extremely coarse sand (>2 mm) (%)	52.02
Very coarse sand (1-2 mm) (%)*	11.33
Coarse sand (0.5 -1 mm) (%)*	8.94
Medium sand (0.25-0.5 mm) (%)*	0
Fine sand (0.10-0.25 mm) (%)*	8.32
Very find sand (0.07-0.10 mm) (%)*	0
Extremely fine sand (< 0.07 mm) (%)*	5.37
Silt (%)	11
Clay (%)	3
Bulk density (g/cm^3)	1.20
Pore space (%)	18.97
Air filled porosity (%)	21.33
Water holding capacity at 0.01 MPa (%)	15.86
pH	7.2
Conductivity (EC) (m mho/cm)	1.59
Nitrate (mg/kg)	65
Phosphorus (mg/kg)	4.5
Potassium (mg/kg)	71
Calcium (mg/kg)	793
Magnesium (mg/kg)	95
Sodium (mg/kg)	65
Sulfur (mg/kg)	94
Boron (mg/kg)	0.7
Iron (mg/kg)	24
Magnesium (mg/kg)	5.2
Zinc (mg/kg)	4.3
Copper (mg/kg)	0.6

Analysis per A&L Great Lakes Laboratories, Inc., Ft. Wayne, IN.
* Analysis per Renewed Earth, Inc., Kalamazoo, MI.

Methods

Plot Location and Preparation. This experiment was conducted on green roof platforms at the Michigan State University Horticultural Teaching and Research Center (HTRC) in Holt, MI. Platforms were constructed as described by VanWoert et al. (2005). Platform plots measured 1.2 x 1.2 m and 0.8 x 2.4 m. Green roof platforms were constructed as per VanWoert et al. (2005a). Green roof substrate (Renewed Earth, Kalamazoo, MI) (Table 3.1) was installed over a XeroFlor XF-105 drainage layer (XeroFlor America, Durham, NC) on June 10, 2009 for the 1.2 x 1.2 m plots and May 5, 2010 for the 0.8 x 2.4 m plots to a depth of 12.7 cm (5 in).

Table 3.2. Composition of Lesco Professional Landscape and Ornamental All-Purpose Fertilizer 14-14-14 (Lesco, Inc., Cleveland, OH).

Nutrient	**Percent Content by Weight (%)**
Total Nitrogen	14.00
Ammoniacal Nitrogen	5.48
Urea Nitrogen	8.55
Phosphate (P_2O_5)	14.00
Soluble Potash (K_2O)	14.00
Total Sulfur	19.40
Free Sulfur	14.40
Combined Sulfur	5.00
Total Iron	0.45
Water soluble Iron	0.005
Total Manganese	0.45
Water soluble manganese	0.05
Chlorine Max	2.00

Three mulching strategies (no mulch, pine bark mulch, and a ground cover of *Sedum album*) in combination with three fertilization rates (two applications of 25, 50, and 100 g/m^2 of Lesco Professional Landscape and Ornamental All-Purpose Fertilizer 14-14-14 (Table 3.2)) (Lesco, Inc, Cleveland, OH) were examined in a three by three factorial design layed out in a randomized complete block with four replicates. Pine bark mulch was spread on June 29, 2010**,** to a depth of 2.5 cm (1 in). *Sedum album* cuttings were taken from the green roof on the Michigan State University Plant and Soil Sciences Building in East Lansing, MI, and 517 g spread on each of the appropriate platform plots on June 24, 2010. These plots received some supplemental watering during the establishment of the *S. album* living mulch. Fertilizer application dates are listed in table 3.3. Weather data was compiled from the Michigan Automated Weather Network (MAWN) station East Lansing/MSUHORT located at the HTRC adjacent to the platforms.

Table 3.3. Important planting and maintenance dates for vegetable production during the 2010 and 2011 growing seasons on green roof platforms.

Activity	2010	2011
Seeds planted	May 3 and 14	May 6
Plugs planted	May 15 and 17	June 16
Pepper plugs planted	May 29	June 30
Irrigation started	June 30	June 7
Irrigation ended	October 3	October 1
Fertilizer application 1	July 1	July 22
Fertilizer application 2	August 9	August 26
Biomass harvest:		
Tomatoes	October 2 and 3	October 1
Beans	September 20	August 29
Cucumbers	August 24	August 29
Peppers	October 2	October 1
Basil	August 22- October 2	October 1
Chives	October 2	October 1

Tomatoes are Roma (VF) tomatoes (*Lycopersicon esculentum*), beans are early contender bush beans (*Phaseolus vulgaris*), cucumbers are bush pickle hybrid cucumbers (*Cucumis sativus*), peppers are Sweetheart® hybrid sweet peppers in 2009 and 2010 and Budapest hot banana peppers in 2011 (*Capsicum annuum*), basil is large-leaf Italian basil (*Ocimum basilicum*), and chives (*Allium schoenoprasum*).

Plant Selection. Vegetable and herbs selected were Roma (VF) tomatoes (*Lycopersicon esculentum*), early contender bush beans (*Phaseolus vulgaris*), bush pickle hybrid cucumbers (*Cucumis sativus*), Sweetheart® hybrid sweet peppers (*Capsicum annuum*) in 2009 and 2010, large-leaf Italian basil (*Ocimum basilicum*), chives (*Allium schoenoprasum*) (Gurney's Seed and Nursery Co., Greendale, IN), and Budapest hot banana peppers (*C. annuum*) (Seedway, Hall, NY) in 2011. They were selected because of their availability, growth habit (determinate or bush variety), and common use in home gardens. These vegetable and herb cultivars were also shown to be successful in an extensive green roof environment in 2009 (Whittinghill, 2012). Vegetables and herbs were planted from seed into 48-cell plug trays in early May of each year (Table 3.3) and grown outdoors, in East Lansing, MI. Budapest hot banana peppers were planted from seed into 98-cell plug trays on April 6, 2011 and grown in a greenhouse until May 24, 2011, then transferred to a lath house at the HTRC.

Due to the limited space available two plants of each type were planted from plugs into green roof platforms (Table 3.3). Plants within each plot were evenly spaced in two rows of six and four rows of three in the 0.8 x 2.4 and 1.2 x 1.2 m plots, respectively. The specific location of each plant was selected randomly in 2010 and remained the same for the 2011 growing season because of the perennial nature of chives. Throughout the growing seasons of 2010 and 2011, all platforms were watered three times daily for 5 min using micro-emitters (Table 3.3).

Data collection and analysis. Tomatoes, beans, cucumbers, and peppers were harvested as they ripened until just before the first frost when all remaining fruit were harvested, combined for each plot, and weighed. The sizes of individual vegetables were measured on the two longest axes using a caliper. Vegetables were divided in to size categories based on USDA standards (USDA, 1991; USDA, 1959; USDA 1936) and size categories were assigned numbers for analysis with 1 representing the smallest size category for each vegetable and 5, 6, and 4 representing the largest size category for tomatoes, beans and cucumbers, respectively. Color of tomatoes was also determined based on USDA standards (USDA, 1991) and color category number (eg. 1 = green, 6 = red) was used for analysis. Potential acceptability of the vegetables to the consumer was rated according to USDA grade standards (USDA, 1991; USDA, 1959; USDA 1936; USDA, 2005). Reasons for unacceptability, such as insect or disease damage, discoloration, or scarring, were recorded. Quality ratings were used to determine crop quality according to USDA standards with lower numbers representing higher quality and 4 indicating a cull (USDA, 1991; USDA, 1959; USDA 1936; USDA, 2005). Number of fruit, total yield in grams and marketable yield in grams based of fruit quality were also recorded at time of harvest. Marketable percent of yield was calculated from total and marketable yield data.

Just before the first frost in 2010 and 2011, whole basil and chive plants were harvested at the substrate surface (Table 3.3). In 2010, basil leaves were evaluated for marketability by removing all leaves and sorting based on the presence of insect damage, discoloration, sun scalding or disease. Basil and chive plant material was weighed fresh, dried at 60 ˚C for 1 wk and weighed again to determine biomass. At the end of each growing season, tomato, bean, cucumber, and pepper plants were also cut even with the soil or substrate surface, and their biomass was determined (Table 3.3). Biomass dry weight was also measured but will not be discussed because it is correlated to biomass wet weight.

Substrate moisture was measured using a theta meter HH1 (Delta-T Devices, Cambridge, England). Three measurements were taken from each plot in the afternoons between September 15 and September 20, 2011. These measurements were taken at the center of the north end, middle and south end of the plots.

Data were analyzed using SAS (Version 9.1, SAS Institute, Cary, NC). Correlations were found between number of fruit and total yield, marketable yield and plant biomass for all vegetables (R^2 from 0.5477 to 0.7147); total yield and marketable yield and plant biomass in all vegetables ($R^2 > 0.8$); and marketable yield and plant biomass ($R^2 > 0.8$). Due to these high correlations results for fruit number, marketable yield and plant biomass will be presented in tables, but not discussed in the text. All data were checked for normality prior to analysis of variance. Non-normal data were analyzed after applying a logarithmic transformation for tomato total yield and pepper total yield, marketable yield and biomass fresh weight and a square root transformation for bean number, total yield, and marketable yield and cucumber biomass fresh weight. Normality issues for the marketable yield data were difficult to resolve due to a large number of zero values across mulch and fertilizer treatments in 2011 so data for each year were analyzed separately. All values are presented as back-transformed data.

Crop yield variables and volumetric moisture content were analyzed using an ANOVA model with mulch treatment, fertilization treatment, and year as fixed effects (PROC MIXED, SAS version 9.1, SAS Institute, Cary, NC). The significance of treatment interactions was determined using a F tests and those interactions that did not have an effect were removed from the analytical model (Table 3.4). Significant differences among treatments were separated using multiple comparisons by LSD with an alpha of 0.05 (PROC MIXED, Version 9.1, SAS Institute). No comparisons among species were made.

Table 3.4. Results for F tests for treatment interactions between mulch type, fertilizer application and year. For all tests α = 0.05. * indicates p < 0.05, ** indicates p <0.01, and *** indicates p < 0.001

Crop Species	Variable	Mulch-Fertilizer-Year	Mulch-Fertilizer	Mulch-Year	Fertililzer-Year
Tomato	**Size**	F = 2.36	F = 3.97**	F = 1.21	F = 3.16*
	Number	F = 0.80	F = 0.87	F = 1.55	F = 5.55**
	Total Yield	F = 0.52	F = 1.65	F = 1.52	F = 2.22
	Marketable Yield	F = 1.62	F = 1.87	F = 0.3	F = 0.45
	Marketable Percent of Yield	F = 2.24	F = 0.37	F = 0.68	F = 0.43
	Biomass Fresh Weight	F = 0.98	F = 0.78	F = 0.43	F = 1.57
Bean	**Grade**	F = 1.73	F = 1.00	F = 0.33***	F = 3.79*
	Number	F = 0.05	F = 0.95	F = 3.61*	F = 0.28
	Total Yield	F = 0.33	F = 1.25	F = 0.78	F = 0.78
	Marketable Yield	F = 0.46	F = 0.61	F = 2.17	F = 1.05
	Marketable Percent of Yield	F = 0.69	F = 0.97	F = 1.31	F = 1.29
	Biomass Fresh Weight	F = 0.33	F = 0.33	F = 5.17**	F = 0.69
Cucumber	**Grade**	F = 0.46	F = 0.4	F = 0.07	F = 0.16
	Number	F = 0.55	F = 1.80	F = 0.28	F = 0.30
	Total Yield	F = 0.89	F = 0.77	F = 1.66	F = 1.22
	Marketable Yield	F = 1.79	F = 2.18	F = 3.59*	F = 5.54**
	Marketable Percent of Yield	F = 0.55	F = 1.13	F = 0.09	F = 0.70
	Biomass Fresh Weight	F = 1.79	F = 0.69	F = 2.86	F = 0.28
Pepper	**Diameter**	NA	F = 0.73	NA	NA
	Grade	NA	F = 1.39	NA	NA
	Number	NA	F = 0.30	NA	NA
	Total Yield	NA	F = 2.04	NA	NA
	Marketable Yield	NA	F = 1.65	NA	NA
	Marketable Percent of Yield	NA	F = 0.52	NA	NA
	Biomass Fresh Weight	NA	F = 0.68	NA	NA
Basil	**Biomass Fresh Weight**	F = 0.19	F = 0.74	F = 3.32	F = 0.19
Chives	**Total Yield**	F = 0.83	F = 0.81	F = 11.87***	F=21.17***

Tomatoes are Roma (VF) tomatoes (*Lycopersicon esculentum*), beans are early contender bush beans (*Phaseolus vulgaris*), cucumbers are bush pickle hybrid cucumbers (*Cucumis sativus*), peppers are Sweetheart® hybrid sweet peppers in 2009 and 2010 and Budapest hot banana peppers in 2011 (*Capsicum annuum*), basil is large-leaf Italian basil (*Ocimum basilicum*), and chives (*Allium schoenoprasum*).

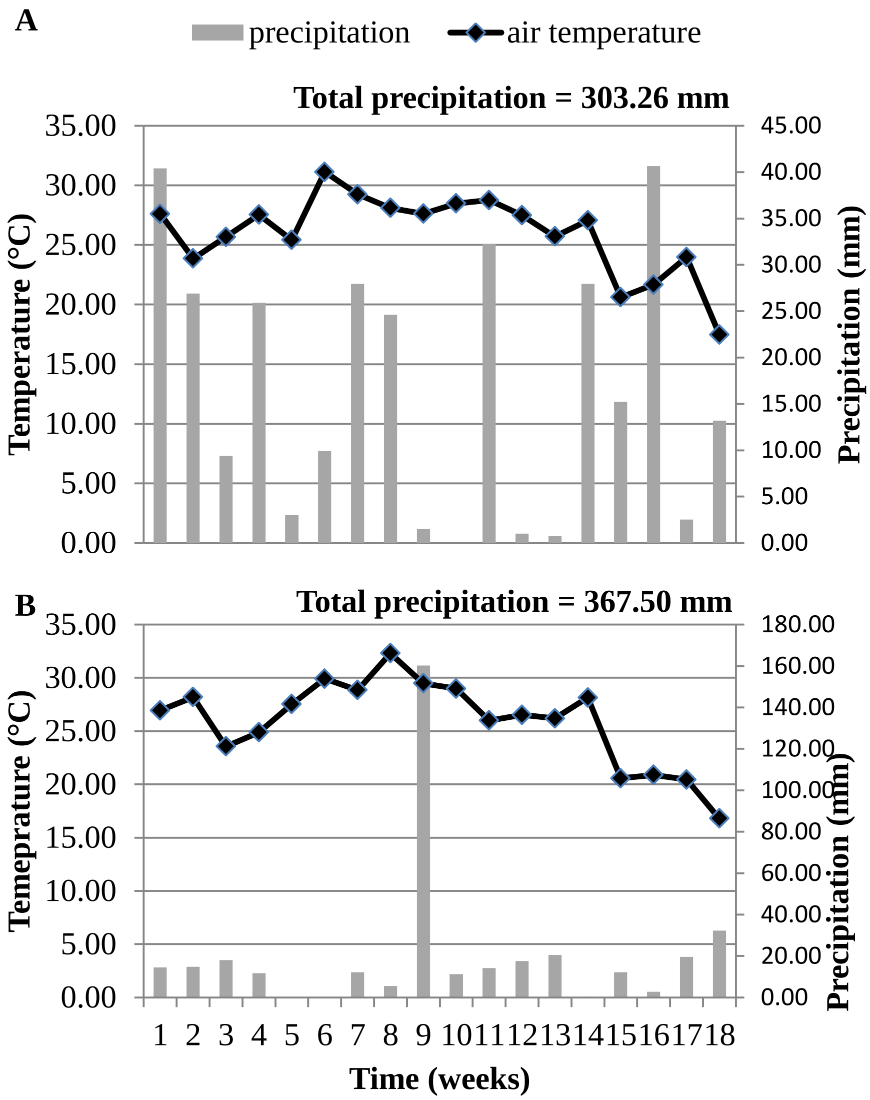

Figure 3.1. Weekly average maximum air temperature in Celsius and weekly total precipitation in mm for the growing seasons of (A) 2010 (May 25-Oct 2) and (B) 2011 (May 29-Oct 1).

Results

Weather. Maximum ambient air temperatures in 2010 and 2011 were similar (Figure 3.1). Minimum ambient air temperatures in 2011 were lower than those in 2010 in September and October but higher in June, July and August. 2011 had more total precipitation that 2010 (Figure 3.1). 2010 had more precipitation in June and September, while 2011 had more precipitation in July and August (Figure 3.1B). Incoming solar radiation was similar for both growing seasons with totals for June, July, August and September of 2.16 and 2.21 million kJ/m^2 for 2010 and 2011, respectively.

Tomatoes. Results for tomato fruit size, color and grade are presented in table 3.5. Mulching had no effect on fruit size in the 100 g/m^2 fertilizer treatment in 2011, fruit color for the 25 and 50 g/m^2 fertilizer treatments in 2010, and fruit grade for any fertilizer treatment in 2011. Fertilizer treatment had no effect on fruit size in the pine bark and live *Sedum* mulch treatments in 2011, fruit color in the no mulch and pine bark mulch in treatments in 2010, and fruit grade for any mulch treatment in 2011. The 2010 25 g/m^2 fertilizer treatment was the only treatment to exhibit a difference in size between the no mulch treatment and both of the other mulch treatments. The live *Sedum* mulch treatment produced redder fruit in the 25 g/m^2 fertilizer treatment than in other fertilizer treatments in 2010. In 2011, however, tomato fruit had redder color in the no mulch 25 g/m^2 and 50 g/m^2 treatments than any other mulch treatment for those fertilizer treatments. In 2010, fruit from the pine bark mulch treatment had lower grade than any other mulch treatment for all fertilizer treatments. Fruit size and color were greater in 2010 than 2011, except for the no mulch and pine bark mulch and 25 g/m^2 treatment combinations and the no mulch 25 g/m^2treatment combination, respectively.

Table 3.5. Quality indices of tomatoes (*Lycopersicon esculentum*) and pod and fruit size of beans (*Phaseolus vulgaris*) and cucumbers (*Cucumis sativus*) in 2010 and 2010 under treatments of no mulch, pine bark mulch, live *Sedum* mulch, and 25, 50, and 100 g/m^2 14-14-14 slow release fertilizer. Tomato sizes, colors and grades based on the USDA standards for fresh tomatoes (USDA, 1991), bean sizes based on the USDA standards for snap beans for processing (USDA, 1959), and cucumber sizes based on the USDA standards for pickling cucumbers (USDA, 1936).

Crop	**Variable**	**Year**	**Treatment**	**25 g/m^2**	**50 g/m^2**	**100 g/m^2**
Tomato	**Fruit Size**	**2010**	**No mulch**	2.1 Ba**A**	2.2 Bab**A**	2.4 Aa**A**
			Pine bark	1.7 Bb**A**	2.3 Aa**A**	2.5 Aa**A**
			Live *Sedum*	1.9 Bb**A**	2.0 ABb**A**	2.1 Ab**A**
		2011	**No mulch**	1.9 Aa**A**	1.6 Bb**B**	1.8 Ba**B**
			Pine bark	1.7 Aa**A**	1.9 Aa**B**	1.7 Aa**B**
			Live *Sedum*	1.6 Ab**B**	1.5 Ab**B**	1.6 Aa**B**
	Fruit Color	**2010**	**No mulch**	4.3 Aa**A**	4.2 Aa**A**	4.3 Aa**A**
			Pine bark	4.4 Aa**A**	4.3 Aa**A**	4.1 Aa**A**
			Live *Sedum*	4.5 Aa**A**	4.1 Ba**A**	3.7 Cb**A**
		2011	**No mulch**	4.3 Aa**A**	3.7 Ba**B**	3.7 Ba**B**
			Pine bark	3.4 Ab**B**	2.9 ABb**B**	2.6 Ba**B**
			Live *Sedum*	2.6 Ab**B**	2.4 Ab**B**	1.8 Bb**B**
	Fruit Grade	**2010**	**No mulch**	3.0 Ab**B**	3.3 Bc**B**	3.0 Ab**B**
			Pine bark	2.8 ABa**B**	2.6 Aa**B**	2.9 Ba**B**
			Live *Sedum*	2.9 Aab**B**	3.0 ABb**B**	3.1 Bc**B**
		2011	**No mulch**	2.0 Aa**A**	2.0 Aa**A**	2.1 Aa**A**
			Pine bark	1.7 Aa**A**	1.8 Aa**A**	2.0 Aa**A**
			Live *Sedum*	1.7 Aa**A**	1.9 Aa**A**	2.1 Aa**A**
Bean	**Pod Size**	**2010**	**No mulch**	2.4 ABa**B**	2.2 Ba**B**	2.6 Aa**B**
			Pine bark	2.5 Aa**B**	2.3 Aa**B**	2.5 Ab**B**
			Live *Sedum*	2.3 Aa**A**	2.4 Aa**B**	2.1 Bb**B**
		2011	**No mulch**	3.4 Aa**A**	3.3 Aa**A**	3.2 Aa**A**
			Pine bark	3.3 ABa**A**	3.5 Ba**A**	3.1 Aa**A**
			Live *Sedum*	3.0 Aa**A**	3.7 Aa**A**	3.4 Aa**A**
Cucumber	**Fruit Size**	**2010**	**No mulch**	2.8 Aa**A**	2.7 Aa**A**	2.9 Aa**A**
			Pine bark	2.7 Aa**A**	2.8 Aa**A**	3.0 Aa**A**
			Live *Sedum*	2.6 Ba**A**	2.7 ABa**A**	2.9 Aa**A**
		2011	**No mulch**	2.9 Aa**A**	2.1 Ba**B**	2.4 ABab**A**
			Pine bark	2.7 ABab**A**	2.1 Ba**B**	3.1 Aa**A**
			Live *Sedum*	1.3 Ab**B**	1.3 Aa**B**	1.9 Ab**B**

Each mean represents observations from 4 replicates. Means were separated using LSD with an alpha of 0.05. Non-bold capital letters in rows indicate differences among fertilizer treatments within mulch treatments and lower case letters in columns indicate differences mulch treatments within fertilizer treatments for each year. Bold capital letters indicates differences between years.

Table 3.6. Yield indices of tomatoes (*Lycopersicon esculentum*) in 2010 and 2011 under treatments of no mulch, pine bark mulch, live *Sedum* mulch, and 25, 50, and 100 g/m^2 14-14-14 slow release fertilizer. Marketability based on USDA standards for fresh tomatoes (USDA, 1991)

Treatment	**Number of Fruit**		**Total Yield (g)**	**Marketable Yield (g)**	**Marketable Percent of Yield (%)**	**Biomass Fresh Weight (g)**
	2010	**2011**				
No mulch	75.2 Aa	41.2 Ba	1833.8 a	1277.1 a	73.2 b	615.3 a
Pine bark	57.4 Aa	36.0 Ba	1522.8 a	1283.3 a	87.1 a	594.9 a
Live *Sedum*	74.4 Aa	27.2 Ba	1446.1 a	1012.1 a	76.5 ab	683.2 a
25 g/m^2	46.4 Ab	29.1 Ba	1084.4 b	925.7 b	88.6 a	444.1 b
50 g/m^2	54.5 Ab	31.3 Ba	1310.0 b	978.1 b	74.7 b	471.0 b
100 g/m^2	106.1 Aa	44.0 Ba	2408.3 a	1668.8 a	73.4 b	978.3 a
2010	N/A	N/A	2296.3 a	1592.0 a	70.9 b	786.5 a
2011	N/A	N/A	905.5 b	789.7 b	87.0 a	475.8 b

Treatment means represent 24 observations, year means represent 48 observations except for number of fruit where treatment means represent 12 observations. Means were separated using LSD with an alpha of 0.05. Letters denote differences among treatments within each factor, capital letters denote differences between years within treatment and are for the transformed data for total yield, marketable yield and biomass fresh weight.

Results for the remaining tomato yield indices are presented in Table 3.6. Fruit number and total yield were not affected by mulching. Fruit number was also not affected by fertilizer treatment in 2011. Application of 100 g/m^2 resulted in higher total, marketable yield, and fresh biomass compared to lower rates. Surprisingly, the 25 g/m^2 fertilizer treatment resulted in a higher marketable percent of yield than treatments with higher fertilizer rates. Marketable percent of yield was higher in the pine bark mulch treatment than the no mulch treatment. Fruit were of a lower grade in 2011 than 2010. Fruit number and total yields were higher in 2010 than 2011, but marketable percent of yield was higher in 2011.

Table 3.7. Harvest indices of beans (*Phaseolus vulgaris*) in 2010 and 2011 under treatments of no mulch, pine bark mulch, live *Sedum* mulch, and 25, 50, and 100 g/m^2 14-14-14 slow release fertilizer. Grade and marketability based on USDA standards for snap beans for processing (USDA, 1959).

Treatment	**Pod Grade**		**Number of Pods**		**Total Yield (g)**	**Marketable Yield (g)**	**Marketable Percent of Yield (%)**	**Biomass Fresh Weight (g)**	
	2010	**2011**	**2010**	**2011**				**2010**	**2011**
No mulch	2.3 Aa	3.3 Ba	47.6 Aa	11.6 Ba	107.0 a	78.6 a	56.3 a	68.8 Aa	21.7 Bb
Pine bark	2.4 Aa	3.3 Ba	37.2 Aa	21.3 Ba	88.4 a	61.8 a	60.4 a	52.9 Aa	42.4 Aa
Live *Sedum*	2.4 Aa	3.5 Ba	38.8 Aa	7.4 Bb	93.8 a	66.9 a	54.2 a	59.2 Aa	13.3 Bb
25 g/m^2	2.4 Aa	3.4 Bab	34.5 Aa	8.5 Bb	78.8 b	53.9 b	55.7 a	49.7 Aa	14.9 Bb
50 g/m^2	2.3 Aa	3.6 Bb	45.2 Aa	14.5 Bab	96.9 ab	70.3 ab	60.7 a	65.1 Aa	28.9 Ba
100 g/m^2	2.4 Aa	3.2 Ba	44.0 Aa	17.3 Ba	113.5 a	83.1 a	54.4 a	66.2 Aa	33.7 Ba
2010	N/A	N/A	N/A	N/A	168.0 a	127.2 a	72.9 a	N/A	N/A
2011	N/A	N/A	N/A	N/A	24.8 b	11.0 b	41.1 b	N/A	N/A

Treatment means represent 24 observations, year means represent 48 observations. Means were separated using LSD with an alpha of 0.05. Lower case letters denote differences among treatments within each factor and capital letters denote differences between years within treatment. Differences are for the transformed data for total yield and marketable yield.

Beans. Results for bean pod size are presented in table 3.5. Pod size was only affected by mulching in combination with the 100 g/m^2 fertilizer treatment in 2010, for which the no mulch treatment produced larger fruit. Pod size was no affected by fertilizer treatment in combination with pine bark mulch in 2010, and the no mulch and live *Sedum* treatment in 2011. When fertilizer did affect pod size, there was only a difference between the 25 g/m^2 and other treatments in combination with the live *Sedum* in 2010, when the 100 g/m fertilizer treatment produced the smallest fruit. Pod size of bean fruit was smaller in 2010 than 2011 for all treatment combinations except the live *Sedum* mulch 25 g/m^2 treatment combination.

The remaining results for bean harvest indices are presented in table 3.7. Mulching had no effect on pod grade, number of pods in 2010, or total yield. Fertilizer treatments also had no effect on pod grade in 2010, number of pods in 2010, and marketable percent of yield. In 2011, pod grades in the 25 g/m^2 fertilizer treatment did not differ from either other fertilizer treatments. There were fewer pods in the live *Sedum* than the other mulch treatments in 2011 and there was no difference between the number of pods from the 50 g/m^2 treatment and the other fertilizer treatments. The effect of fertilizer was similar on total yield. All harvest indices were higher in 2010 than in 2011.

Cucumbers. Results for cucumber fruit size are presented in table 3.5. Mulching had no effect on fruit size in combination with any fertilizer treatment in 2010 and in combination with the 50 g/m^2 fertilizer treatment in 2011. Fertilizer treatments had no effect on fruit size in combination with the no mulch and pine bark mulch treatments in 2010 and the live *Sedum* in

2011. In 2010, fruit growing in the live *Sedum* mulch were larger in the 100 g/m^2 treatment than the 25 g/m^2 treatment. In 2011, fruit sizes in the no mulch and pine bark were smaller in the 50 g/m^2 fertilizer treatments and smaller in the live *Sedum* than other mulches in combination with the 25 and 50 g/m^2 fertilizer treatments. Fruit were smaller in 2011 than in 2010 in all mulch treatments within the 50 g/m^2 fertilizer treatment and all fertilizer treatments within the live *Sedum* mulch.

Table 3.8. Harvest indices of cucumbers (*Cucumis sativus*) in 2010 and 2011 under treatments of no mulch, pine bark mulch, live *Sedum* mulch, and 25, 50, and 100 g/m^2 14-14-14 slow release fertilizer. Grades and marketability based on the USDA standards for pickling cucumbers (USDA, 1936).

Treatment	**Fruit Grade**	**Number of Fruit**	**Total Yield (g)**	**Marketable Yield (g)**		**Marketable Percent of Yield (%)**	**Biomass Fresh Weight (g)**
				2010	**2011**		
No mulch	3.6 a	5.1 a	730.6 a	456.8 Ab	22.7 Ba	26.3 a	65.9 a
Pine bark	3.6 a	5.4 a	753.8 a	693.1 Aa	18.5 Ba	31.7 a	73.0 a
Live *Sedum*	3.6 a	5.7 a	782.1 a	569.3 Aab	26.5 Ba	30.8 a	53.8 b
25 g/m^2	3.7 a	4.6 b	548.0 b	365.4 Ab	15.2 Ba	22.5 a	51.3 b
50 g/m^2	3.5 a	5.6 ab	703.5 b	661.9 Aa	16.6 Ba	32.0 a	64.9 ab
100 g/m^2	3.6 a	6.0 a	1015.1 a	691.9 Aa	35.9 Ba	34.2 a	76.4 a
2010	3.3 a	8.1 a	1169.0 a	N/A	N/A	49.0 a	93.4 a
2011	3.9 b	2.7 b	342.0 b	N/A	N/A	10.1 b	35.0 b

Treatment means represent 24 observations, year means represent 48 observations, except for marketable yield from which treatment means represent 12 observations. Means were separated using LSD with an alpha of 0.05. Lower case letters denote differences among treatments within each factor and capital letters denote differences between years within treatment. Biomass fresh weight differences are for the transformed data.

Results for the remaining harvest indices for cucumbers are presented in table 3.8. Mulching had no effect on fruit grade, number of fruit, total yield, or marketable percent of yield and fertilizer treatments had no effect on fruit grade and marketable percent of yield. There was a positive dose response of fertilizer treatments on number of fruit and total yield. All harvest indices were higher in 2010 than in 2011.

Table 3.9. Harvest indices of Budapest hot banana peppers (*Capsicum annuum*) for the 2011 growing season under treatments of no mulch, pine bark mulch, live *Sedum* mulch, and 25, 50, and 100 g/m^2 14-14-14 slow release fertilizer. Grades and marketability based on the USDA standards for sweet peppers (USDA, 2005).

Treatment	**Fruit Diameter (cm)**	**Fruit Grade**	**Number of Fruit**	**Total Yield (g)**	**Marketable Yield (g)**	**Marketable Percent of Yield (%)**	**Biomass Fresh Weight (g)**
No mulch	2.4 a	2.3 a	4.8 a	87.7 a	70.9 a	76.1 a	47.4 a
Pine bark	2.2 a	2.7 ab	3.5 a	48.0 a	35.2 b	62.2 ab	38.6 a
Live *Sedum*	1.9 b	3.0 b	3.9 a	29.1 b	20.2 b	44.8 b	37.5 a
25 g/m^2	1.9 b	3.2 b	2.0 c	12.8 c	7.8 c	41.7 b	24.1 c
50 g/m^2	2.2 ab	2.5 a	3.9 b	44.5 b	34.8 b	75.4 a	40.1 b
100 g/m^2	2.4 a	2.5 a	6.7 a	107.5 a	83.7 a	66.1 ab	71.2 a

Treatment means represent 12 observations. Means were separated using LSD with an alpha of 0.05. Letters denote differences among treatments; for total yield, marketable yield and biomass fresh weight denote differences are for the transformed data.

Pepper. Yields from Sweetheart® in 2010 were extremely limited (data not shown). Statistical analysis was not performed because we believe that this lack of success was due to the cultivar choice and not the experimental treatments. The Budapest hot banana peppers were more successful in 2011. Results for all harvest indices are presented in table 3.9. Mulching had no effect on number of fruit. Fruit growing in the live *Sedum* mulch had smaller diameter, higher grades, lower total yields, and lower marketable percent of yield than fruit from the no mulch treatments. Fertilizer treatment had a positive dose response on all harvest indices measured.

Basil. Pine bark mulch produced plants with lower biomass fresh weight than the other two mulch treatments and plants from the 100 g/m^2 fertilizer treatment had the highest biomass fresh weight of any fertilizer treatment (Table 3.10). There were no differences in the biomass fresh weights of 2010 and 2011 or in marketable percent of biomass of any mulch treatment or any fertilizer treatment (Table 3.10).

Table 3.10. Biomass fresh weight in grams of basil (*Ocimum basilicum*) for the 2010 and 2011 growing season and marketable fresh weight yield in grams and marketable percent of biomass fresh weight for the 2010 growing seasons under treatments of no mulch, pine bark mulch, live *Sedum* mulch, and 25, 50, and 100 g/m^2 14-14-14 slow release fertilizer.

Treatment	**Biomass Fresh Weight (g)**	**Marketable Yield (g)**	**Marketable Percent of Biomass (%)**
No mulch	1098.1 a	146.2 a	11.3 a
Pine bark	730.1 b	58.8 b	8.4 a
Live *Sedum*	984.7 a	95.1 ab	10.2 a
25 g/m^2	619.5 c	67.3 b	9.1 a
50 g/m^2	862.6 b	102.4 ab	11.2 a
100 g/m^2	1330.8 a	130.5 a	9.6 a
2010	968.3 a	NA	NA
2011	906.9 a	NA	NA

Treatment means represent 24 observations, year means represent 48 observations. Means were separated using LSD with an alpha of 0.05.Letters denote differences among treatments within each factor for the transformed data.

Table 3.11. Fresh weight yield in grams for chives (*Allium schoenoprasum*) in 2010 and 2011 under treatments of no mulch, pine bark mulch, live *Sedum* mulch, and 25, 50, and 100 g/m^2 14-14-14 slow release fertilizer.

Treatment	**2010**	**2011**
No mulch	27.7 Ba	649.5 Aa
Pine bark	23.3 Ba	623.4 Aa
Live *Sedum*	32.6 Ba	455.0 Ab
25 g/m^2	21.5 Bb	434.2 Ab
50 g/m^2	29.0 Bab	449.8 Ab
100 g/m^2	33.1 Ba	843.8 Aa

Each mean represents 12 observations. Means were separated using LSD with an alpha of 0.05. Capital letters in rows denote differences among years within treatments and lower case letters in columns indicate differences among treatments within year for each factor.

Chives. In 2010, mulching had no effect on yield (Table 3.11). Fresh weight yield of the live *Sedum* mulch treatment was lower than the other mulch treatments in 2011. Fertilizer treatments had a positive dose response on yield in both 2010 and 2011 (Table 3.11). Fresh weight yields were higher in 2011 than in 2010 (Table 3.11).

Substrate moisture. There was no difference between volumetric moisture content of the no mulch and live *Sedum* mulch treatments (0.303 and 0.295 m^3/m^3, respectively). The pine bark mulch treatment had the lowest volumetric moisture content at 0.270 m^3/m^3.

Discussion

Overall the vegetable species examined performed better in 2010 than 2011. Although the overall temperature trends in 2010 and 2011 were similar, the 2011 growing season exhibited more weather extremes. The growing season started cool and was followed by a warm, dry June. Although July was the wettest month in 2011, precipitation came in a few very large storm events and was followed by another dry period. 2010 had more consistent precipitation throughout the growing season with more frequent moderate storm events. These weather differences likely resulted in harsher growing conditions in 2011 despite irrigation.

Total yields from this study were improved over those previously found on green roof platforms at MSU. High yields from this study were higher than those reported by Whittinghill (2012) (Table 3.12). These yields were within the range of those expected based on recommended planting density (Swiader and Ware, 2002) and reported harvest area and yields (USDA, 2011) for tomato, bean and cucumber but not pepper (Table 3.12). This suggests that more intensive management can improve yields on extensive green roofs to those comparable to in-ground conventional agriculture. The persisting low yields of peppers suggests that further research on pepper cultivars is necessary before their production on extensive green roofs will be as productive as in-ground production.

Table 3.12. Estimated yield in grams per plant for the highest yields achieved in this study, from chapter 2 (Whittinghill, 2012), and from reported growing area and yield data reported by the USDA (2011) and recommended planting densities based on row and plant spacing (Swiader and Ware, 2002).

Vegetable	**Estimated from this study**		**Yields from Ch 2 (g/plant) (Whittinghill, 2012)**	**Estimated yield (g/plant) from USDA (2011) and Swaider and Ware (2002)**
	Treatment or Year	**Yield (g/plant)**		
Tomato	Mulch treatments	916.9	Green roof platform, 2010: 285.5	744.93-1347.08
	100 g/m^2	1,204.1		
	2010	1,148.1		
Bean	Mulch treatments	53.5	Green roof platform, 2010: 40.6	14.85-22.90
	100 g/m^2	56.7		
	2010	84.0		
Cucumber	Mulching treatments	391.0	Green roof platform, 2010: 213.05	281.36-1067.24
	100 g/m^2	507.55		
	2010	584.5		
Pepper	No mulch and pine bark mulch	43.8	Green roof platform, 2011: 15.49	712.62-564.88
	100 g/m^2	53.7		

Estimated yields from this study derived by dividing the indicated mean by 2 plants. USDA (2011) yield estimates derived by dividing the USDA reported yield/m^2 by estimated plant densities derived from Swiader and Ware (2002).

Mulch treatment. The most common outcome of the mulch treatments across fertilizer treatments, growing seasons and vegetable or herb species was that there was no significant difference between the productivity of crops for any of the mulch treatments. The second most common outcome was that there was no difference between the no mulch and pine bark mulch treatments. There are however some exceptions. For tomato, the live *Sedum* mulch treatment produced the largest fruit (Table 3.5) and pine bark mulch produced the best quality fruit under some fertilizer treatments and the higher marketable percent of yield (Tables 3.3 and 3.4). *Sedum* species reduce surface and near surface temperatures on a green roof compared to bare substrate (Butler and Orians, 2011; Durhman et al., 2006; Wolf and Lundholm, 2008), which may have enabled fruit to grow larger before ripening. The pine bark mulch, however has a similar color to the green roof substrate, and may not have reduced temperatures as much as the *Sedum* mulch while still preventing evaporation from the substrate enabling the production of better quality fruit. Pine bark mulch also showed promising results for bean plant biomass production (Table 3.7), and cucumber size, marketable yield and plant biomass production (Tables 3.3 and 3.7) although not clearly above the other mulch treatments. This could suggest that the mulch's ability to moderate moisture losses through the substrate were beneficial, but its effect on surface and near surface temperatures as compared with the other mulch treatments were not as beneficial. Further research including more extensive measurements of substrate moisture levels and near surface, surface and substrate temperatures would determine more specifically how pine bark mulch affected crop growth and production.

When combined with 100 g/m^2 fertilizer applications, *Sedum* mulch also acted as a competitor with tomato, bean, and cucumber, but only affected some aspects of production such as color (Table 3.5), size of fruit (Tables 3.3), and biomass production (Tables 3.5 and 3.6). Peppers were affected negatively by live *Sedum* mulch more than the other vegetables, with all variables except number of fruit lower than the other mulch treatments (Table 3.8). It suggests that the live *Sedum* mulch either acted as a competitor, decreasing crop production, or that the resulting changes in surface and near surface temperatures reduced temperatures below those favored by peppers. The perennial chives was not affected by mulch treatment during the first year of production, but the *Sedum* mulch appeared to act as a competitor, reducing yields, during the second year of production. Other research into the use of live cover crops between rows of low-till systems have also shown mixed results in the performance of cabbage, snap beans (Masiunas et al., 1997) tomato (Akintoye et al., 2004), broccoli (Chase and Mbuya, 2008), and peppers (Chellemi and Russkopf, 2004). In these cases living mulches could act as competitors with the desired crop under some management systems. In the case of living *Sedum*, it has been shown to act as a competitor with herbaceous plants on a green roof under conditions when water is not limiting (Butler and Orians, 2011). As irrigation was supplied to the vegetables and herbs in this study, it is likely that enough irrigation was not a limiting factor. It is also possible that *Sedum* was better able to make use of the supplied fertilizer than the vegetable and herb crops. *Sedum album* has a very shallow, but dense root system and it is possible that the fertilizer was taken up by the *S. album* as it was released before it reached the deeper, less dense roots of the vegetable and herb species. It is likely that this form of living mulch should be avoided in chives and Budapest hot banana peppers production.

The lack of difference between the volumetric moisture content of the no mulch and live *Sedum* mulch treatments and lower volumetric moisture in the pine bark mulch treatment was an unexpected result. It has been well established that the use of mulch can reduce moisture loss through the growing substrate (Ham, et al., 1993; Masiunas et al., 2003; Ngouajio and Ernest, 2001, Tanner, 1974; Tarara, 2000). One explanation for the discrepancy between this and previous research is the timing of volumetric moisture content measurements. Measurements were taken in September of 2011, when temperatures had cooled down, become cloudy and there were shorter periods of time between precipitation events. These weather conditions may have resulted in conditions where the substrate under all mulch treatments could become and stay saturated. Irrigation throughout the experiment may have also reduced differences between mulch treatments because of greater water availability. Further experimentation with the use of mulches in extensive green roof vegetable production where measurements are taken throughout the growing season could reveal greater differences in the volumetric moisture content of substrate under mulch treatments. Measurements throughout the growing season under irrigated conditions may also show the extent to which mulch reduces water loss through evaporation under conditions where water is less limiting.

Fertilizer treatment. The most frequent outcome of the fertilizer treatments was that they had no effect on crop quality or production. The second most frequent outcome was that the 100 g/m^2 treatment outperformed at least one of the other fertilizer treatments. Both basil and chives are crops with yields dependent on vegetative growth. Nitrogen increases vegetative growth, so higher yields in the 100 g/m^2 fertilizer treatment would be expected.

There were, however some difference among crops and among measured variables within crops. The 25 g/m^2 fertilizer treatment either outperformed other fertilizer treatments or performed second best for tomato color (Table 3.5) and marketable percent of yield (Table 3.6), bean size and grade (Tables 3.3 and 3.5), and cucumber size (Table 3.5). There were also a number of instances where the 50 g/m^2 performed as well as the 100 g/m^2 treatment, but better than the 25 g/m^2 treatment. Comparing recommended N needs of each vegetable and herb species based on soil tests performed by the Michigan State University Soil and Plant Nutrient Laboratory (East Lansing, MI) and recommended application rates from Warncke et al. (2004) for mineral soils (Table 3.13), with the amounts nutrients provided by the fertilizer treatments (Table 3.13) can explain some of these differences. The amount of phosphorus (P) and potassium (K) applied by the 25 g/m^2 fertilizer treatment were adequate for tomato, bean,

Table 3.13. The nutrient recommendations (g/m^2) for each vegetable and herb crop based on soil testing performed by the Michigan State University Soil and Plant Nutrient Laboratory (MSUSPNL) (East Lansing, MI) and nutrient application recommendations from Warncke et al (2004) and the nutrients supplied (g/m^2) by the applications of 25, 50 and 100 g/m^2 of a Lesco Professional Landscape and Ornamental All-Purpose Fertilizer 14-14-14.

		Nitrogen (g/m^2)	**Phosphorus (g/m^2)**	**Potassium (g/m^2)**
Crop	**Tomatoes**	13.45	0.0363	0.206
	Beans	4.483	0.138	0.0575
	Cucumber	11.209	0.0312	0.06084
	Peppers	11.209	0.0454	0.1183
	Ground cover (from MSUSPNL) as a proxy for basil and chives	4.88-9.76	10.74	6.835
Treatment	**25 g/m^2**	3.5	3.5	3.5
	50 g/m^2	7	7	7
	100 g/m^2	14	14	14

Tomatoes are Roma (VF) tomatoes (*Lycopersicon esculentum*), beans are early contender bush beans (*Phaseolus vulgaris*), cucumbers are bush pickle hybrid cucumbers (*Cucumis sativus*), peppers are Sweetheart® hybrid sweet peppers in 2009 and 2010 and Budapest hot banana peppers in 2011 (*Capsicum annuum*), basil is large-leaf Italian basil (*Ocimum basilicum*), and chives (*Allium schoenoprasum*).

cucumber, and pepper. This may have been the influencing factor enabling the 25 g/m^2 fertilizer treatment to produce redder tomato and higher quality tomato, bean, and cucumber. The 50 g/m^2 treatment only supplied adequate N for bean, explaining why unlike the other vegetable species, this treatment rather than the 100 g/m^2 treatment provided the best yields. Only the 100 g/m^2 treatment provided adequate N for tomato, cucumber, and pepper. It is possible that fertilizer with a higher N content, but similar P and K content could be applied in lower rates and yield quality crops. Further research should be performed on fertilizer composition to improve the efficiency of nutrient use by the crop plants. In a larger scale production system it may also be possible to fertilize parts of the roof differently based on specific crop needs which would also increase the efficiency of fertilizer use and minimize the impacts on runoff quality.

Conclusions

Use of more intensive management practices improved yields of tomato, bean and cucumber plants enough that they fell within the range of those expected from in-ground conventional agriculture. This supports the theory that extensive green roof agriculture is a productive use of rooftop space. The use of pine bark mulch or live *Sedum* mulch in the production of tomatoes, beans, and cucumbers did not have a clear impact on production in this two-year study. It would appear that neither of these mulches would be necessary for successful production of these crops on an extensive green roof in Michigan, provided that the roofs were irrigated. There are other mulch alternatives not examined here, such as straw or paper pulp mulch, which could improve production and warrant examination. The live *Sedum album* mulch used in this study appeared to act as a competitor with Budapest hot banana peppers and chives and should not be used in production of those crops. Although it did affect some aspects of tomato, bean, and cucumber production, it need not be avoided in production of those crops in Michigan. A lack of difference between the volumetric moisture content of the mulch treatments examined in this study is more likely to be attributed to irrigation and weather patterns than mulch treatments and measuring over a longer period of time during the growing season in future research would better reveal the effects of various mulch treatments on substrate moisture content in green roof vegetable production.

There were few differences between fertilizer treatments. This may be attributed to the lowest fertilizer applications rates supplied adequate P and K for most crops in the study, but inadequate N in all but the largest fertilizer applications. That adequate N was supplied by only the 100 g/m^2 fertilizer treatment explains why, in most cases, when there was a difference in fertilizer treatments, this produced the best crops. This suggests that a fertilizer should be used that will supply higher amounts of N per unit of P and K supplied to the plants. Further research on fertilizers with different compositions including micronutrients would reveal the best mix of N, P, and K to apply to vegetable production in extensive green roof agriculture. For the cases where the 50 and 100 g/m^2 fertilizer treatments were not different, examination of runoff water nutrient levels could determine which is more appropriate to use from an environmental standpoint. This would help prevent the occurrence of the negative impacts of fertilizer over application.

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CHAPTER FOUR:

Stormwater runoff quantity and quality from two traditional and one vegetable producing extensive green roof

Abstract

Stormwater retention is one of the well-studied benefits of green roofs. A roof's ability to retain stormwater depends on factors such as the intensity and duration of the rain event as well as substrate depth, substrate moisture content, and vegetation type, health, density and water use efficiency. Extensive green roofs used for crop production will differ from more traditional *Sedum* and prairie covered extensive green roofs in plant density and water use efficiency, but the impact on stormwater retention has not been well studied. Three vegetation types (unfertilized *Sedum* and native prairie species mixes, and a fertilized vegetable and herb species mix) were compared for stormwater runoff quantity over three growing seasons, and stormwater runoff quality and substrate moisture content during one growing season. The prairie covered green roofs had the greatest increase in runoff as precipitation increased, almost three times that of *Sedum* or vegetable producing green roof treatments. Vegetation treatment had no effect on runoff nitrate-nitrogen (NO_3^-) concentrations, but NO_3^- concentrations decreased over the course of the growing season. Runoff phosphorus (P) concentrations also decreased over time in the *Sedum* and prairie treatments, which were lower than P concentration from the vegetable crop system throughout the growing season. This is likely a result of the different amounts of NO_3^- and P applied to the vegetable treatment and the needs of the crop plants in that treatment. Vegetation treatment had no effect on substrate moisture content. The similarities in water retention and water quality between vegetable producing extensive green roofs and *Sedum* green roofs suggest that vegetable production with careful nutrient management will not have a negative impact on the ability of extensive green roofs to retain stormwater or manage stormwater quality.

Introduction

Green roofs have been shown to have numerous benefits. These include reduced air and noise pollution, increased habitat and biodiversity, increased roof lifespan, stormwater retention, energy savings and mitigation of the urban heat island effect (Alexandri and Jones, 2008; Barrio, 1998; Carter and Jackson, 2007; Getter and Rowe, 2006; Getter et al., 2007; Loder and Peck, 2004; Saiz et al., 2006; VanWoert et al., 2005a; Wong et al., 2003). Stormwater retention and energy savings are two benefits that have come to the forefront in light of growing concerns about greenhouse gas emissions and difficulties in managing water flow off impervious surfaces in urban areas. Both are impacting policy in the United States (Carter and Keeler, 2008, Lipton, 2005). Green roofs have been shown to retain between 52 and 100% of precipitation depending on the intensity and duration of the rain event and depending on slope, substrate depth, substrate moisture content, evapotranspiration rates, and vegetation (Czemiel Berndtsson, 2010; Getter et al., 2007; Hathaway et al., 2008; Rowe, 2011; VanWoert et al., 2005a). This has been well studied for roofs planted with a more typical selection of green roof plants, such as *Sedum spp*. Agricultural production on green roofs is of growing interest and is in practice in many cities around the world (Whittinghill and Rowe, 2011). There is however no literature on the impacts of agricultural production on the ability of a green roof to retain stormwater or the impact on runoff water quality, which could be of great concern due to nutrient supplementation necessary for crop production (Whittinghill and Rowe, 2011).

Many other factors influence the ability of a green roof to provide benefits in the form of storm water retention. These include water use efficiency of the vegetation and evapotranspiration rates, microclimatic conditions including near-surface, and plant temperatures, absorption of incoming radiation by the substrate surface and roof vegetation, emission of sensible heat from the substrate and roof vegetation, plant health and survival, the density of vegetation cover, shade cover provided by the vegetation, exposure and color of the soil surface and soil moisture content (Durhman et al., 2006; Ham et al., 1991; Heilman et al., 1996; Tanner, 1974; VanWoert et al., 2005a, 2005b). These variables can be explored by examining vegetation covers that have varying water use efficiencies, growth habits, numbers of plants and amounts of bare substrate. In this experiment two traditional extensive green roof vegetation covers, a *Sedum spp.* mix and a native prairie species mix will be compared with a vegetable and herb mix.

Vegetable and herb plants also have very different water needs than most species usually found on extensive green roofs. Sedums, for example require very little water over the course of a growing season (Durham et al., 2006; VanWoert et al., 2005b), while tomatoes are very sensitive to changes in water availability. Dry spells can delay maturity of the tomato crop and decrease yield and crop quality (Abdul-Baki and Teasdale, 2007). Other herbaceous plants examined for growth on extensive green roofs were also found to be drought intolerant with limited survival in the absence of irrigation (Durham et al., 2006; Monterusso et al., 2005). This may include vegetable and herb crops. For standard in ground production, irrigation recommendations are 3.05 to 12.19 mm/day (0.12-0.48 in/day) for tomatoes, 5.08 mm/day (0.2 in/day) for garden beans, and 3.62 to 7.26 mm/day (0.14 to 0.29 in/day) for cucumbers (Swiader and Ware, 2002). The difference in the water needs of sedums and herbaceous plants can be traced to their photosynthetic adaptations. Sedums exhibit crassulacean acid metabolism (CAM) under drought conditions and reduce transpiration water loss during the day by opening their stomata at night (Getter and Rowe, 2006). Prairie species are often a mix species exhibiting C3 and C4 photosynthesis and many vegetable and herb species exhibit C3 photosynthesis and possess no mechanism for reducing daytime transpiration water loss. On green roofs that are not irrigated *Sedum spp.* and many prairie species also have the ability to go dormant during periods of drought, during which time transpiration is reduced to near zero.

These three vegetation covers also exhibit very different growth habits. *Sedum spp.* are succulent ground covers and tend to remain close to the ground without large leaf structures, while prairie species exhibit a wide variety of growth forms from broad-leafed rosettes to tall grasses. Vegetable and herb species also exhibit wide variety in growth forms, although many are broad leafed and many grow with either a bush or vine shape. The taller and broad leafed growth forms of prairie and vegetable and herb species could enable denser canopy cover, than the lower growing *Sedum spp*.

It is also expected that sedums and prairie species will completely cover the rooftop area on a mature green roof, shading the substrate and minimizing evaporation (Durhman et al., 2006; VanWoert et al., 2005b; Wolf and Lundholm, 2008). Vegetables and herbs however, are often planted with empty space between them. The substrate may remain exposed for the entire growing season if the crop canopy does not close. These differences in coverage of the substrate also translate into differences in number of plants. With complete coverage the *Sedum spp.* and prairie roofs with have many plants per unit area, while vegetable crops typically have densities of between 2 and 35 plants/m^2, depending on the variety (Swiader and Ware, 2002). These differences could lead to very different energy balances on green roofs created using the two different types of vegetation, specifically where substrate moisture content, and therefore storm water retention are concerned.

The main objective of this experiment was to determine what, if any, differences exist in stormwater retention and substrate moisture content of extensive green roofs planted with vegetables and herbs for food production, and those planted with more typical mixes of either Sedum or prairie species. This was achieved by monitoring runoff from three green roof types over three growing seasons. Substrate moisture measurements and runoff water samples were taken during one growing season to evaluate differences in substrate moisture content and runoff water quality. As the capacity of a green roof to retain storm water is related to the substrate moisture content at the onset of a precipitation event and the water holding capacity of the substrate (VanWoert et al., 2005a) it was expected that green roofs planted with vegetables and herbs would retain more storm water than the green roofs planted with either the sedum or prairie mixes, but have lower substrate moisture content. It is also expected that runoff water from the green roof planted with vegetables and herbs would have higher concentrations of nutrients because fertilizer must be used to provide adequate nutrients for vegetable and herb production.

Methods

Experimental design. Three landscape systems were examined; (1) a *Sedum* mix, hereafter referred to as sedum green roof, containing *Sedum acre* 'Golden Carpet', *S. album*, *S. kamtschaticum*, and *S. spurium* 'Summer Glory'; (2) a native prairie mix, hereafter referred to as prairie green roof, containing by percentage of seed weight: 0.5% *Achillea millefolium* (yarrow), 2% *Asclepias tuberosa* (butterflyweed), 1% *Asclepias syriaca* (common milkweed), 4% *Aster novae-angliae* (New England aster), 0.5 % *Aster pilosus* (hairy aster), 3% *Coreopsis lanceolata* (sand tickseed), 1% *Desmodium canadense* (showy tick trefoil), 2% *Echinacea purpurea* (purple coneflower), 0.5% *Kuhnia eupatoroides* (false boneset), 2% *Lupinus perennis* (wild lupine), 4% *Monarda fistulosa* (burgamot), 0.5% *Oenothera biennis* (common evening primrose), 2% *Penstemon digitalis* (foxglove beardtongue), 4% *Ratibida pinnata* (grayheaded coneflower), 6%

Rudbeckia hirta (blackeyed Susan), 1% *Rudbeckia triloba* (three-lobed coneflower), 1% *Silphium integrifolium* (rosinweed), 1% *Silphium laciniatum* (compass plant), 4% *Solidago rigida* (stiff goldenrod), 3% *Solidago speciosa* (showy goldenrod), 2% *Verbena stricta* (hoary vervain), 12% *Andropogon gerardii* (big bluestem), 6% *Elymus canadensis* (Canada wild rye), 5% *Panicum virgatum* (switch grass), 20% *Schizachyrium scoparium* (little bluestem), 12% *Sorghastrum nutans* (Indian grass); and (3) vegetable and herb mix, hereafter referred to as vegetable green roof, of *Lycopersicon esculentum* (Roma (VF) tomatoes), *Phaseolus vulgaris* (early contender bush beans), *Cucumis sativus* (bush pickle hybrid cucumbers), *Capsicum annuum* (Sweetheart® hybrid sweet peppers) in 2009 and 2010, *Ocimum basilicum* (large-leaf Italian basil), *Allium schoenoprasum* (chives) (Gurney's Seed and Nursery Co., Scarlet Tanager LLC., Greendale, IN), and *C. annuum* (Budapest hot banana peppers) (Seedway, Hall, NY) in 2011. These vegetable and herb species were selected because of their availability, growth habit (determinate or bush variety), and common use in home gardens.

The experiment was conducted on green roof platforms at the Michigan State University Horticultural Teaching and Research Center (HTRC) in East Lansing, MI, during three growing seasons from 2009 to 2011. Green roof platforms were constructed as per VanWoert et al. (2005a). Green roof substrate (Renewed Earth, Kalamazoo, MI) (Table 4.1) was installed on June 10, 2009 to a depth of 10.5 cm over a XeroFlor XF-105 drainage layer (XeroFlor America, Durham, NC). These platforms contained three 0.8 x 2.4 m sections. In order to control for edge effect, the green roof types were alternated between the three sections in the four replicate platforms.

Table 4.1. Initial physical and chemical properties of substrate

Component	Unit
Total Sand (%)	86
Extremely coarse sand (>2 mm) (%)	52.02
Very coarse sand (1-2 mm) (%)*	11.33
Coarse sand (0.5 -1 mm) (%)*	8.94
Medium sand (0.25-0.5 mm) (%)*	0
Fine sand (0.10-0.25 mm) (%)*	8.32
Very find sand (0.07-0.10 mm) (%)*	0
Extremely fine sand (< 0.07 mm) (%)*	5.37
Silt (%)	11
Clay (%)	3
Bulk density (g/cm^3)	1.20
Pore space (%)	18.97
Air filled porosity (%)	21.33
Water holding capacity at 0.01 MPa (%)	15.86
pH	7.2
Conductivity (EC) (m mho/cm)	1.59
Nitrate (mg/kg)	65
Phosphorus (mg/kg)	4.5
Potassium (mg/kg)	71
Calcium (mg/kg)	793
Magnesium (mg/kg)	95
Sodium (mg/kg)	65
Sulfur (mg/kg)	94
Boron (mg/kg)	0.7
Iron (mg/kg)	24
Magnesium (mg/kg)	5.2
Zinc (mg/kg)	4.3
Copper (mg/kg)	0.6

Analysis per A&L Great Lakes Laboratories, Inc., Ft. Wayne, IN.
* Analysis per Renewed Earth, Inc., Kalamazoo, MI.

The sedum and prairie treatments were sown from seed on May 16, 2009. The sedum was planted by mixing 1.2 g of seed with 400 mL of sand and broadcasting the mixture over each plot by hand. Similarly, the prairie mix was also hand broadcast at a rate of 2.83 g of seed per plot. Plots were covered with shade cloth until seeds germinated.

Table 4.2. Planting and maintenance dates of the vegetable green roofs for the growing seasons of 2009, 2010 and 2011.

Action	2009	2010	2011
Seeds planted	May 9	May 3 and 14	May 6
Plugs planted	May 29	May 15 and17	June 16
Pepper plugs planted	May 29	May 29	June 30
Irrigation started	May 29	June 30	June 7
Irrigation ended	October 2	October 3	October 1
Fertilizer application 1	June 13	July 1	July 22
Fertilizer application 2	N/A	August 9	August 26

Due to the limited space available two plants of each vegetable and herb species were evenly spaced in two rows of six with the specific location of each plant randomly selected at the beginning of the 2009 growing season. Vegetables were sown into 48-cell plug trays and grown outside, in East Lansing, MI (Table 4.2) and then transplanted in the platforms as plugs (Table 4.2). *Capsicum annuum* (Budapest hot banana peppers) were sown from seed into 98-cell plug trays on April 6, 2011 and grown in a greenhouse until May 24, 2011, then transferred to a lath

Table 4.3 Composition of Lesco Professional Landscape and Ornamental All-Purpose Fertilizer 14-14-14 (Lesco, Inc., Cleveland, OH).

Nutrient	Percent Content by Weight (%)
Total Nitrogen	14.00
Ammoniacal Nitrogen	5.48
Urea Nitrogen	8.55
Phosphate (P_2O_5)	14.00
Soluble Potash (K_2O)	14.00
Total Sulfur	19.40
Free Sulfur	14.40
Combined Sulfur	5.00
Total Iron	0.45
Water soluble Iron	0.005
Total Manganese	0.45
Water soluble manganese	0.05
Chlorine Max	2.00

house at the HTRC, until they were planted in the platforms (Table 4.2). Platforms were watered three times daily for 15 min using overhead sprinklers throughout the 2009 growing season and three times daily for 5 min using micro-emitters throughout the 2010 and 2011 growing seasons (Table 4.2). Lesco Professional Landscape and Ornamental All-Purpose Fertilizer 14-14-14 (Table 4.3) (Lesco, INC, Cleveland, OH) was applied to the green roof platforms at a rate of 25 g/m^2 once in 2009 and twice during 2010 and 2011 (Table 4.2).

Data collection and analysis. Stormwater runoff was measured using TE525WS tipping bucket rain gauges (Campbell's Scientific, Inc., Logan, UT) that were connected to a CR10X datalogger (Campbell's Scientific, Inc., Logan, UT) using 3 AM16T multiplexers (Campbell's Scientific, Inc., Logan, UT). A guard constructed from 25.4 cm round plastic plant saucers was placed around the outlet of the aluminum troughs to prevent precipitation falling outside each platform area from entering the tipping buckets. Rainfall was measured using an additional tipping bucket adjacent to the platforms. The datalogger was programmed to collect rainfall and runoff amounts from tipping buckets every minute and to summarize totals at 15 min intervals during the growing seasons of 2009, 2010 and 2011. Rain events were determined to be independent from each other if they were separated by more than 6 hrs and runoff had stopped before that time had passed. Rain events were categorized into three intensity groupings; light (< 2 mm), medium (2 to 10 mm) and heavy (> 10 mm). Data on ambient weather conditions were taken from the Michigan Automated Weather Network (MAWN) station East Lansing/MSUHORT located at the HTRC adjacent to the platforms.

Samples of the first 125 mL (63.66 mm) of runoff were collected five times during the 2011 growing season. One sample was taken before the first fertilizer application on July 11, 2011. Two samples were then taken after the first fertilizer application on August 16, and

August 26, 2011. Two samples were also taken after the second fertilizer application on September 17, and October 2, 2011. All samples were analyzed for nitrate-nitrogen (NO_3^-) and phosphorus (P). Analysis was performed by the Michigan State University Soil and Plant Nutrient Laboratory in East Lansing, MI.

Soil moisture was measured using a theta meter HH1 (Delta-T Devices, Cambridge, England). Three measurements were taken from each plot, at the center of the north end, middle and south end, on five afternoons between September 15 and September 20, 2011. Platforms were set at a 2% slope with the top edge of the high end 0.9 m above ground and oriented with the low end of the slope facing south to maximize sun exposure.

Data were analyzed using SAS (Version 9.1, SAS Institute, Cary, NC). Non-normal data were analyzed after applying a square root transformation for NO_3^- and logarithmic transformations for P and substrate moisture content. All values are presented as back-transformed data. Influence diagnostics were used to identify outliers, which were removed if they were deemed unrepresentative. Multiple linear regression was performed on precipitation events comparing runoff to precipitation for reach vegetation treatment (PROC GLM, Version 9.1, SAS Institute, Cary, NC). Mean NO_3^- and P content were analyzed using an ANOVA model with landscape system and time as fixed effects. Mean volumetric moisture content of the substrate was analyzed using an ANOVA model with landscape system and measurement location within the plot as fixed effects. Significant differences were determined using multiple comparisons by LSD with an alpha of 0.05 (PROC MIXED, Version 9.1, SAS Institute, Cary, NC).

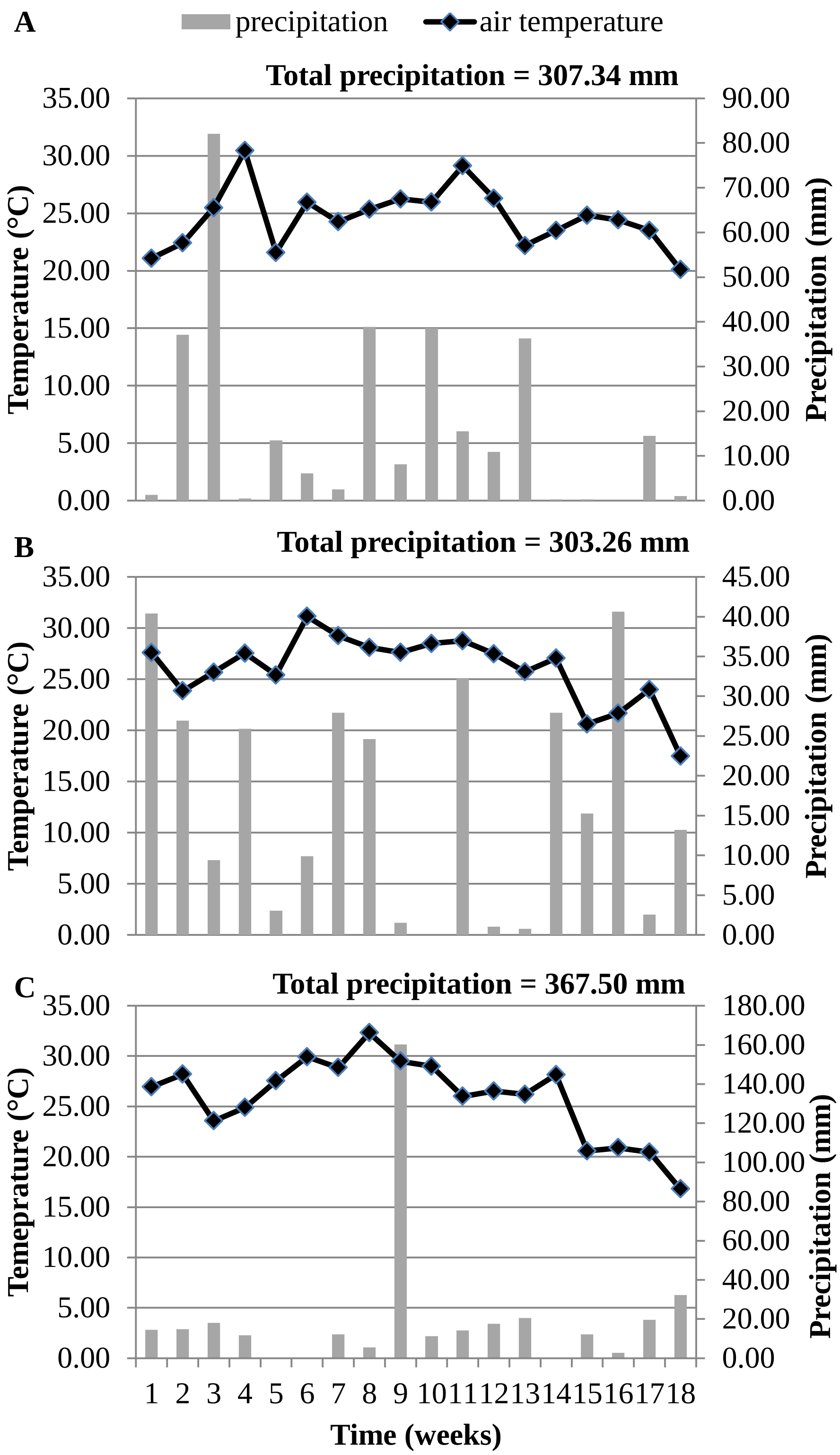

Figure 4.1. Weekly average maximum air temperature in Celsius and weekly total precipitation in mm for the growing seasons of (A) 2009 (May 31-Oct 2) (B) 2010 (May 25-Oct 2) and (C) 2011 (May 29-Oct 1).

Results

Weather. Maximum and minimum ambient air temperatures and measured precipitation for each month during the three growing seasons (2009, 2010, and 2011) are shown in Figure 4.1. During 2009, maximum temperatures in May, July and August were lower than the following two growing seasons and similar maximum temperatures were recorded during 2010 and 2011. Minimum temperatures were also lower in May, September, and October in 2009, than those recorded in 2010 and 2011. Total precipitation was greatest during 2011, however, 2009 experienced more precipitation during June and August than 2010 and 2011 but lower in September and July, respectively (Figure 4.1). Incoming solar radiation was similar for all three growing seasons with totals for June, July, August and September of 2.24, 2.16, and 2.21 million kJ/m^2 for 2009, 2010, and 2011, respectively.

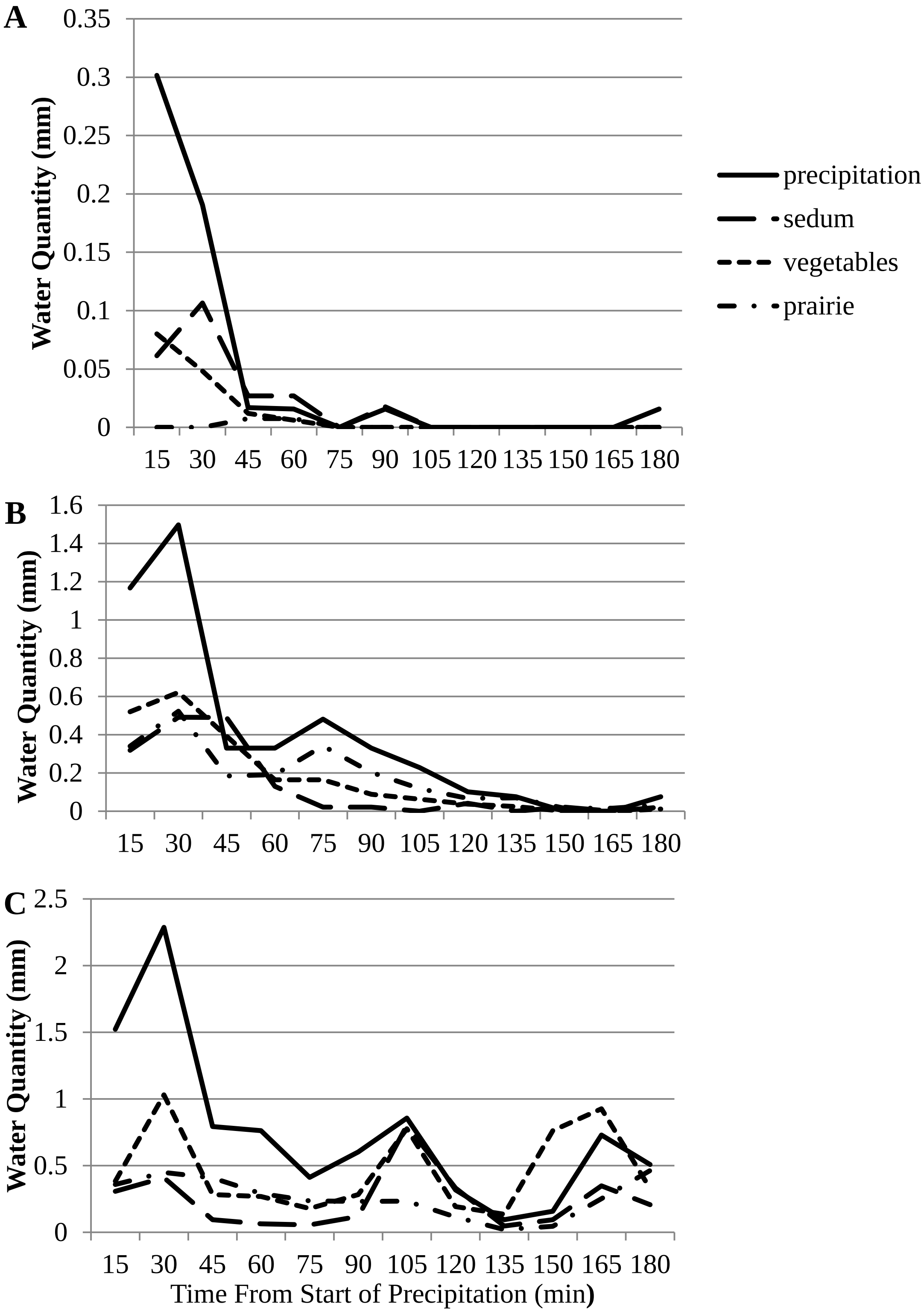

Figure 4.2. Runoff hydrographs of precipitation events of (A) light, (B) medium, and (C) heavy rainfall. Rain events recorded at 15 min intervals. Values are averages of measurements taken from all tipping buckets for each treatment within each precipitation event size category over the growing seasons of 2009, 2010, and 2011.

Water retention. Initial runoff from the platforms was lower than the amount of precipitation (Figure 4.2). There was, however, no clear delay in runoff or difference between vegetation types. There was a significant interaction between precipitation and vegetation type (F = 13.857, p <0.0001, α = 0.05). Regression lines for sedum and vegetable green roofs were very similar with much higher amounts of runoff per mm precipitation than the regression line predicted for the prairie green roof (Figure 4.3). This indicates that as rainfall increased, the amount of runoff from the sedum and vegetable green roofs increased at similar rates, while the amount of runoff from the prairie green roofs increased at a slower rate. No relationship was found between reference potential evapotransporation or treatment and the amount of runoff from irrigation events (data not shown).

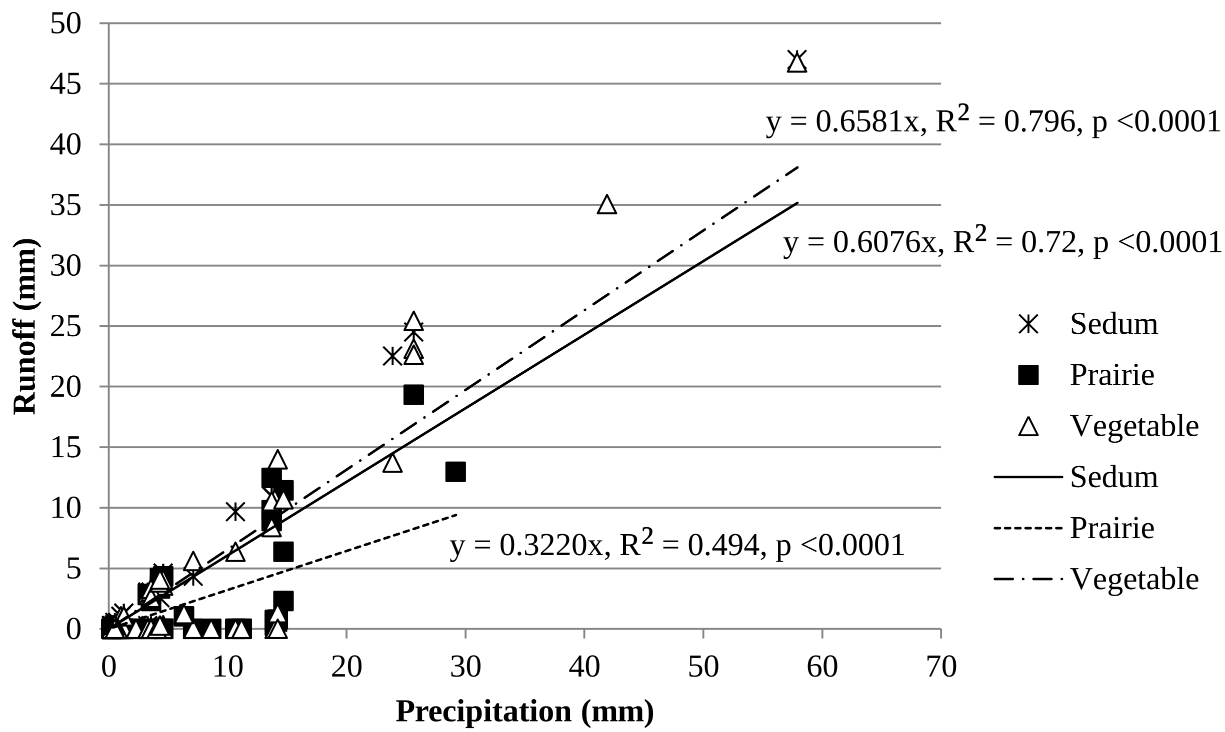

Figure 4.3. Multiple linear regressions of precipitation and runoff for the growing seasons of 2009, 2010 and 2011. Each marker represents a single observation.

Table 4.4. Nitrate concentrations (mg/L) in the first 125 mL of runoff water taken in 2011 from extensive green roofs vegetated with a mix of *Sedum* species, a native prairie mix, and a fertilized vegetable and herb garden before the first fertilizer application and 3 and 5 weeks after the first and second fertilizer applications.

		Nitrate content (mg/L)
Treatment	**Sedum**	0.14 a
	Prairie	0.15 a
	Vegetable	0.22 a
Time	**Initial**	0.30 a
	3 weeks after first fertilizer application	0.13 b
	5 weeks after first fertilizer application	0.29 a
	3 weeks after second fertilizer application	0.04 c
	5 weeks after second fertilizer application	0.04 c

Means represent 20 observations for treatments and 12 observations for time. Means were separated using LSD with an α of 0.05. Letters indicate significant differences for each factor.

Water quality. Initial NO_3^- and P concentrations can be attributed to the organic matter present in the green roof substrate (Table 4.1). The treatment-time interaction had no effect on NO_3^- concentration in runoff ($F = 0.37$, $p > 0.5$, $\alpha = 0.05$). Vegetation treatment had no effect on runoff water NO_3^- concentrations (Table 4.4). Nitrate concentration decreased over time with higher initial values and values after the first fertilizer application than after the second fertilizer application (Table 4.4). NO_3^- concentrations for the sedum and vegetable green roof treatments and three weeks after the first fertilizer application were lower (Table 4.4). This did not affect significant differences among green roof treatments, but NO_3^- concentrations three weeks after the first fertilizer application were lower than those for the initial and five weeks after the first fertilizer application sample values, but still higher than both samples taken after the first fertilizer application (Table 4.4).

Phosphorus concentration in the first 125 mL runoff water was higher earlier in the growing season for the sedum and prairie green roofs (Table 4.5). The vegetable green roof exhibited the highest P concentrations three weeks after the second fertilizer applications, but the P concentration of the initial sample time was not different from any other sample time (Table 4.5). Five weeks after the first fertilizer application P levels in runoff from the vegetable plots were higher than those of the other two roof types which did not differ from each other (Table 4.5). This remained so for the rest of the sample times (Table 4.5).

Table 4.5. Phosphorus concentrations (mg/L) in the first 125 mL of runoff water taken in 2011 from extensive green roofs vegetated with a mix of *Sedum* species, a native prairie mix, and a fertilized vegetable and herb garden before the first fertilizer application and 3 and 5 weeks after the first and second fertilizer applications.

	Initial	**3 weeks after first fertilizer application**	**5 weeks after first fertilizer application**	**3 weeks after second fertilizer application**	**5 weeks after second fertilizer application**
Sedum	0.15 Aa	0.08 Aa	0.04 Bb	0.03 Bb	0.02 Bb
Prairie	0.12 Aa	0.07 ABa	0.04 BCb	0.02 Cb	0.03 Cb
Vegetable	0.23 ABa	0.14 Ba	0.15 Ba	0.44 Aa	0.21 Ba

Means represent 4 observations. Means were separated using LSD with an α of 0.05. Capital letters in rows indicate significant differences among sample times within green roof treatments and lower case letters in columns indicate differences among green roof treatments within sample times.

Substrate Moisture. The treatment-location of measurement interaction had no effect on volumetric moisture content ($F = 1.18$, $p > 0.5$, $\alpha = 0.05$). There was no difference between the volumetric moisture content of any of the green roof treatments (Table 4.6). Volumetric moisture content was different in each of the locations measured and was highest at the south (low) end of the plots and lowest and the north (high) end of the plots (Table 4.6).

Table 4.6. Volumetric moisture content (m^3/m^3) of extensive green roofs vegetated with a mix of *Sedum* species, a native prairie mix, and a fertilized vegetable and herb garden.

Treatment/Location	Volumetric Moisture Content (m^3/m^3)
Sedum	0.298 a
Prairie	0.287 a
Vegetable	0.303 a
Top	0.271 c
Middle	0.296 b
Bottom	0.321 a

Means represent 60 observations. Means were separated using LSD with an α of 0.05. Letters denote significant differences.

Discussion

Water retention. The lack of clear delay in runoff in the hydrographs was unexpected. VanWoert et al (2005a) found delays of up to 55 min depending on the size of the rain event. Getter et al. (2007) however found negligible delays in runoff similar to those in Figure 4.3. Getter et al. (2007) speculated that this discrepancy was due their use of a steeper slope than some used by VanWoert et al. (2005a). This study used the same 2 % slope use by VanWoert et al., (2005a), so this explanation does not apply here. Another explanation was the moisture conditions of the substrate before each rain event (Getter et al., 2007). This explanation fits as plots were irrigated throughout the summer, so substrate moisture content before each rain event could have been higher than in either of those two studies.

The lower amount of runoff per mm of precipitation for the prairie green roof (Figure 4.4) could be explained by the different microclimates on each of the three green roof types. The prairie green roof did not have complete coverage of the substrate like the sedum green roof, enabling greater evaporation from the substrate surface and more plants than the vegetable green roof, implying greater amounts of transpiration than from vegetables. Both of these factors have been shown to enable the substrate to dry out to a greater extent between rain events and therefore hold more water when the next rain event occurs, thus reducing runoff (Dunnett et al., 2008; Nagase and Dunnett, 2012; VanWoert et al., 2005a; Voyde et al., 2010). Although greater evapotranspiration, and therefore greater water retention capacity, was expected on the vegetable green roof than the sedum green roof, it appears that the vegetable green roof did not retain as much runoff as the sedum green roof (Figure 4.4). Irrigation was supplied to the green roof and may have effected how stormwater was retained by the three vegetation types. Other research has shown that irrigation can reduce the amount of stormwater retained for larger precipitation events (Scholl et al., 2011).

Another explanation for the differences in stormwater retention is plant morphologies. Studies have shown that taller and wider plants and plants with broader leaves intercept more rainfall, adding water storage not included in the physical properties of the substrate (Dunnet et al., 2008; Nagase and Dunnet, 2012). The prairie green roof, not only has more plants than the vegetable green roof, but a greater variety of growth forms including tall grasses and lower lying rosette forms which will have a greater chance of intercepting water before it reaches the substrate. Dunnett et al. (2008) and Nagase and Dunnet (2012) also found that denser root morphologies hold more water. Both the prairie green roof and the sedum green roof had more plants and greater coverage, suggesting a more extensive root system, which would enable both to capture more water than the vegetable green roof. This may account for the difference between the regression lines of the sedum green roof and the vegetable green roof. The differences between the regression lines for the sedum and vegetable green roofs were not however very large (Figure 4.4), suggesting that production of vegetables on extensive green roofs will not negatively affect stormwater retention as compared with sedum green roofs. Runoff comparisons from rooftop scale agricultural and more traditional extensive green roofs will determine if these results are applicable on that scale.

Table 4.7. Nitrogen and Phosphorus supplied to the vegetable green roof treatment from the 25 g/m^2 Lesco Professional Landscape and Ornamental All-Purpose Fertilizer 14-14-14 applied twice during the growing season as compared with nutrient recommendations based on substrate tests and plant nutrient use (Warncke et al, 2004).

	Nitrogen from fertilizer (g/m^2)	**Recommended Nitrogen (g/m^2)**	**Phosphorus from fertilizer (g/m^2)**	**Recommended Phosphorus (g/m^2)**
***Lycopersicon esculentum* (Roma (VF) tomatoes)**	3.5	13.45	3.5	0.036
***Phaseolus vulgaris* (early contender bush beans)**	3.5	4.48	3.5	0.019
***Cucumis sativus* (bush pickle hybrid cucumbers)**	3.5	11.21	3.5	0.031
***Capsicum annuum* (Sweetheart® hybrid sweet peppers)**	3.5	11.21	3.5	0.045

Water quality. Differences in runoff quality among treatments and over time can be explained by comparing plant nutrient needs with the amount of fertilizer applied to the vegetable plots, and previously researched patterns in nutrient leaching as green roofs age. The 25 g/m^2 of fertilizer applied to the vegetable green roof did not provide adequate N as compared with application recommendations based on plant nutrient uptake (Warncke et al., 2004) (Table 4.7). It is then possible the N added by the fertilizer was taken up by the vegetable and herb plants, not allowing extra runoff. The P provided by the fertilizer was however more than necessary for the vegetable plants (Table 4.7). This would explain why P content of the vegetable green roof runoff was higher than the other treatments (Table 4.6). These runoff P concentrations remained high throughout the growing season, a known phenomenon when controlled release fertilizers are used (Emilsson et al., 2007). The pattern in declining NO_3^- and

P content of the prairie and sedum green roofs can be explained through the aging process of green roofs. Nutrients leach out of green roofs in runoff, but nutrient leaching often declines over time as the amount of organic matter in the roof substrate decreases and the readily soluble nutrients have already been leached out of the roof substrate (Czemiel Berndtsson, 2010).

All NO_3^- concentrations observed were well below the EPA 10 mg/L guideline for drinking water (USEPA, 2012a). All P concentrations also fell below the Michigan 1 mg/L guideline for point sources (MDEQ, 2012). Other Midwestern states have more stringent P guidelines ranging from 0.012 mg/L for lakes with trout in Minnesota to 0.09 mg/L for shallow lakes and reservoirs in Minnesota (USEPA, 2012b). When compared with grey water concentrations of NO_3^-, concentrations in this study are lower than those found in grey water form bathrooms (0.28-6.3 mg/L), laundries (0.4-2 mg/L), or kitchens (0.3-5.8 mg/L), but within the low end of concentrations found in grey water form mixed sources (0-4.9 mg/L)(Eriksson et al., 2002). Concentrations of P from the sedum and prairie roofs are lower than those found in any grey water source (0.06-74 mg/L) (Eriksson et al., 2002) starting the fifth week after the first fertilizer application. Runoff from the vegetable roofs contains P concentrations in the low end of reported grey water concentrations (Eriksson et al., 2002). When compared with runoff concentrations of NO_3^- (0.07-0.8 mg/L) and P (0.01-3 mg/L) from other runoff quality studies performed on green roofs (Czemiel Berndtsson, 2010), the highest concentrations found in this study (0.29 mg/L of NO_3^- and 0.44 mg/L of P) are moderate. When compared to NO_3^- and P losses in container nursery production, which can range be as high as 7.55 and 1.4 mg/L, respectively (Warsaw et al., 2009), the values found in this experiment are quite low.

Further experimentation on different types of fertilizers with different nutrient concentrations may reveal a fertilizer nutrient combination where vegetable crops are supplied enough of the essential nutrients without allowing excess to be leached off the roof. Adding amendments to the substrate may be another method of reducing nutrient leaching from the roof that was not explored in this study. For example, amending green roof substrates with biochar, has been shown to increase retention of many nutrients including NO_3^- (Beck et al., 2011). Our study also only examined nutrient concentrations in the first 125 mL (63.66 mm) of runoff, but total NO_3^- and P quantities can be made. NO_3^- runoff for all three growing seasons was 1.91 mg, 1.16 mg of which came from the vegetable green roofs (Table 4.8) and the estimated total P runoff for all three growing seasons was 1.39 mg, 1.02 mg of which came from the vegetable green roofs (Table 4.9). When compared to total losses of up to 133 mg/pot (Fare et al., 1994) and 39.4 $mg/m^2 \cdot day$ (Warsaw et al., 2009) of NO_3^- and 9 $mg/m^2 \cdot day$ (Warsaw et al., 2009) of P, the total nutrient loads estimated for this study are quite small.

Table 4.8. Estimated total nitrate loads in milligrams for runoff from extensive green roofs vegetated with a mix of *Sedum* species, a native prairie mix, and a fertilized vegetable and herb garden during the growing seasons of 2009-11.

Treatment/Location	2009	2010	2011	Total
Sedum	0.27	0.15	0.00	0.42
Prairie	0.01	0.30	0.02	0.33
Vegetable	0.56	0.59	0.01	1.16
Total	0.84	1.04	0.03	1.91

Table 4.9. Estimated total phosphorus loads in milligrams for runoff from extensive green roofs vegetated with a mix of *Sedum* species, a native prairie mix, and a fertilized vegetable and herb garden during the growing seasons of 2009-11.

Treatment/Location	2009	2010	2011	Total
Sedum	0.08	0.13	0.00	0.21
Prairie	0.00	0.15	0.01	0.16
Vegetable	0.38	0.63	0.01	1.02
Total	0.46	0.91	0.02	1.39

Substrate Moisture. The lack of difference between volumetric moisture content of the treatments may, in part, be explained by the fact that these roofs were irrigated and by the weather conditions at the time measurements were taken. Irrigation events never really allowed the substrate to become completely dry. Also, substrate moisture measurements were taken in September 2011, when the air temperature lows were lower than earlier in the season (Figure 4.1C) and there were more frequent small rain events. It is possible that the substrate in all three treatments remained saturated during the time measurements were taken. Results may have been much different in July when temperatures were higher and precipitation less frequent. Season long substrate moisture measurements may reveal differences during such times of year and patterns in volumetric moisture content over the course of a growing season. Analysis of patterns over the course of a growing season could enable more informed efficient use of irrigation by reducing applied irrigation during cool wet periods were precipitation provides vegetable plants with adequate water. The difference in volumetric moisture content between locations measured within a plot is consistent the expected drainage of water down the slope of the roof.

Conclusions

Results of this study show that there are no adverse effects of cultivating vegetable and herb crops and herb crops on extensive green roof in Michigan on stormwater retention. This is encouraging as it could mean that agricultural rooftops will be just as beneficial to reducing the stormwater runoff load of an urban area as other green roofs, but measurements taken on full scale roofs will be needed to confirm that these results are applicable on that scale. There was no difference between the volumetric moisture content of the three green roof types. This was unexpected because of assumed differences in plant coverage and differences in plant physiologies, but may be a result of applied irrigation. Some of it may be due to the irrigation and weather at the time measurements were taken. Further examination of substrate moisture over the course of the growing season may reveal subtle differences between the green roof types.

Effects on runoff quality are less clear. Under the fertilization regimen used for this study, there was no increase in runoff NO_3^- concentrations in the vegetable green roof over the other, more traditional green roof types, but there was an increase in P. This is likely due to the mismatch in crop plant nutrient needs and the amounts of those nutrients supplied with the fertilizer used. Better understanding of this impact of crop production on green roofs could be achieved with a wider look at fertilizers with different nutrient concentrations, both conventional and organic, and analysis of more N types in green roof runoff. Further examination of concentrations of all N types, paired with the types of N found in fertilizers used could also create a broader picture of how fertilizer use efficiency impacts runoff quality. Finally, further examination of total nutrient loads form the roofs could reveal differences between vegetation types not found in this study that may be important to the process of minimizing the impact of fertilizers on runoff water quality.

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CHAPTER FIVE:

Quantifying carbon sequestration of various green roof and landscape systems

Abstract

Interest in reducing carbon emissions and credit trading programs has been increasing, but in order to enforce regulations or participate in credit trading programs organizations must first understand their landscapes and how they sequester carbon and how long they will store that carbon. A great deal of research has been done on natural and agricultural landscapes, and some on urban forests and street trees. Little work has been done on ornamental landscapes, which could potentially contain a large quantity of carbon. This study compared the carbon concentrations of nine in ground and three green roof landscape systems of varying complexity to determine their potential to sequester carbon. Soil or substrate samples were analyzed prior to planting in 2009 and soil/substrate, below- and above-ground biomass were analyzed at the end of the 2010 and 2011 growing seasons. Landscape systems containing more woody structures, such as the three shrub systems and the herbaceous perennials and grasses had higher carbon content than other landscape systems. The native prairie mix also had high carbon content, because of the high volume of plant biomass in that landscape system. The vegetable and herb garden and vegetable green roof sequestered a moderate amount of carbon. The *Sedum* and prairie green roofs contained less carbon than their counterpart in-ground landscape systems, suggesting that although green roofs do sequester a small amount of carbon, greater benefit can be achieved in ground level landscape systems. Ornamental landscapes have good potential for carbon sequestration but management practices can affect their net carbon sequestration and the permanence of the carbon sequestered, which could make their inclusion in carbon credit programs difficult.

Introduction

Growing concerns about global climate change and atmospheric carbon levels have led to an increase in legislation and programs designed to reduce carbon emissions and remove carbon from the atmosphere. Some such initiatives include the Kyoto Protocol, which required participating countries to reduce carbon emissions to 5% below 1990 levels by 2012 (UNFCCC, 1997), and the Chicago Climate Exchange (CCX), which also calls for emissions reductions, but enables those unable to meet the goals of the program to purchase credits from other participants (CCX, 2009). There have also been other trading programs focused on greenhouse gasses including nitrogen oxides (Clark et al., 2005; Clark et al., 2006) and sulfur dioxide (Clark et al., 2006). Individuals or groups wishing to participate in such programs must understand how their landscapes sequester carbon.

There are large differences in the ability of landscapes to sequester carbon. These differences are functions of species diversity, plant physiological characteristics, species abundance, and climate (Kucharik et al., 2003; Matamala et al., 2008; Sandermann and Amundson, 2009; Tilman et al., 2006). Landscapes with greater species diversity have been shown to sequester larger amounts of carbon (Tilman et al., 2006) and landscape age can impact the amount of carbon sequestered. As landscapes age increases in litter, microbial and root biomass have been recorded (Matamala et al., 2008) as well as increases in woody biomass (Fang et al. 2007) depending on the type of vegetation. Management can also play a large role in not only how much carbon can be sequestered (Balesdent et al., 2000; Fang et al., 2007; Wu, et al., 2008), but also in their ability to offset carbon emissions. Cultivation in an agricultural setting decreases the amount of carbon contained in a landscape by reducing soil organic matter (Balesdent et al., 2000), microbial and root biomass (Matamala et al., 2008), and often large woody plants such as forests were converted to smaller herbaceous crop plants (Rhodes et al., 2000). More intensive management, which often entails greater carbon emissions, of ornamental landscapes and forests changes the balance between carbon emitted and carbon sequestered. This leads to a point in time when more carbon is emitted due to management practices than can be taken up by the landscape during the course of a year (Nowak et al., 2002).

Much of the research conducted on carbon sequestration has been in natural landscapes and agricultural lands, but recently the focus has been shifted to include urban landscapes such as forests and urban street trees. Frequently these settings are more managed and are exposed to different conditions than natural landscapes. Due to higher temperatures in urban areas than surrounding rural areas, urban forests tend to be greater sinks for carbon during the growing season, but a greater source of carbon emissions during the winter than their rural counterparts (Awal et al., 2010). Management highlights the issues of quality and permanence that are important when considering a landscape as potential carbon credit. Different land owners tend to manage differently (Bigsby, 2009) and it has been suggested that when an urban tree dies and is replaced no new carbon is sequestered, but the tree merely offsets the carbon being released by the decaying dead tree (Nowak et al., 2002). This may also be true of ornamental landscapes composed of shrubs and herbaceous plants. The ornamental horticulture industry is comprised of land in the United States for both production and planting and the planting substrate typically used has greater carbon content than field soils (Marble et al., 2011). However, the amount of carbon contained in the plants, and what happens after they are transplanted from the nursery to the landscape is not well understood.

This study will build on the work of Miller (2012) and Getter et al. (2009). The work done by Miller (2012) focuses on determining the amount of carbon contained in shrubs, herbaceous perennials, grasses and ground covers grown in the nursery industry. Getter et al. (2009) found that several extensive green roofs located in Michigan and Maryland stored an average of 162 g C/m^2 in above-ground biomass with variation due to roof age and substrate depth. In a second study, a 6 cm deep sedum based roof contained 375 g C/m^2 in above- and below-ground biomass and substrate organic matter. They speculated that differences between their findings and those of others examining the issue of carbon sequestration may be due to the age of the plants in the study, and differences between the physiology of succulents used on green roofs and the plants used in previous research on forests and agriculture.

The objectives of this study are twofold and attempt to determine how plants examined by Miller (2012) sequester carbon after planting and address some gaps in knowledge found by Getter et al (2009). The first objective is to quantify the amount of carbon sequestered by ornamental and green roof landscapes of varying complexity. The second objective is to then determine what if any differences in carbon sequestration exist between the landscape systems and differences in carbon sequestration between green roof landscapes and similar landscape systems at ground level.

Methods

This study examined the carbon content of thirteen ornamental landscape systems of varying complexity over the course of three years at the Michigan State University Horticulture Teaching and Research Center (HTRC) in East Lansing, MI. Of these, nine landscape systems were grown at ground level and four of these were repeated in elevated roof platforms (hereafter referred to as green roof platforms). A randomized complete block design was used with four replicates per treatment.

Landscape Systems at Ground Level. The landscape systems examined at ground level included (1) Kentucky bluegrass lawn, (2) native prairie mix, (3) succulent rock garden consisting of *Sedum*, (4) woody ground covers, (5) herbaceous perennials and grasses, (6) deciduous shrubs, (7) broad-leaf evergreen shrubs, (8) narrow-leaf evergreen shrubs, and (9) vegetable and herb garden. The ground level plots were prepared by first treating the area to be used with glyphosate (Roundup®, Monsanto, St. Louis, MO). Once the existing vegetation was dead the area was deep tilled by spading on May 25, 2009. The ground area was then divided into 2.4 x 2.4 m (8 x 8 ft) plots separated by 1.5 m (5 ft) of turf. Two of these plots were divided into three 0.8 x 2.4 m sections for the vegetable plots, but only the four edge sections were used. These plot sizes were chosen because they matched the sizes of the existing green roof platforms used for the corresponding landscape systems in the study. Overhead irrigation was supplied for the 2009 growing season while plants were establishing. No irrigation was provided during the

Table 5.1 Composition of Lesco Professional Landscape and Ornamental All-Purpose Fertilizer 14-14-14 (Lesco, Inc., Cleveland, OH).

Nutrient	Percent Content by Weight (%)
Total Nitrogen	14.00
Ammoniacal Nitrogen	5.48
Urea Nitrogen	8.55
Phosphate (P_2O_5)	14.00
Soluble Potash (K_2O)	14.00
Total Sulfur	19.40
Free Sulfur	14.40
Combined Sulfur	5.00
Total Iron	0.45
Water soluble Iron	0.005
Total Manganese	0.45
Water soluble manganese	0.05
Chlorine Max	2.00

2010 and 2011 growing seasons. The vegetable plots were fertilized with Lesco Professional Landscape and Ornamental All-Purpose Fertilizer 14-14-14 (Table 5.1) (Lesco, INC, Cleveland, OH) at a rate of 10 g/m^2 once in 2009 and twice during 2010 and 2011 (Table 5.2).

Table 5.2. Planting and maintenance dates of vegetable and herb garden and vegetable green roof plots for the 2009, 2010 and 2011 growing seasons.

Activity	**2009**	**2010**	**2011**
Seeds planted	May 9	May 3 and 14	May 6
Plugs planted:			
Green roof platforms	May 29	May 15	June 16
At grade	May 29	May 27	June 19
Pepper plugs planted:			
Green roof platforms	May 29	May 29	June 30
At grade	May 29	May 29	July 6
Irrigation On	May 29	June 30	June 7
Irrigation Off	October 2	October 3	October 1
Fertilizer application 1			
Green roof platforms	June 13	July 1	July 22
At grade	June 13	July 1	July 22
Fertilizer application 2			
Green roof platforms	N/A	August 9	August 26
At grade	N/A	August 12	August 26
Biomass harvest:			
Ocimum basilicum	October 1 and 2	August 22-October 2	October 1 and 2
Allium schoenoprasum	October 1 and 2	October 2	October 1 and 2
Phaseolus vulgaris	October 1 and 2	September 20	August 29
Cucumis sativus	October 1 and 2	August 24	August 29
Capsicum annuum	October 1 and 2	October 2	October 1 and 2
Lycopersicon esculentum	October 1 and 2	October 2 and 3	October 1 and 2

Landscape Systems on Green Roof Platforms. Four of the landscape systems, (10) extensive green roof consisting of *Sedum* (hereafter referred to as *Sedum* green roof), (11) extensive green roof consisting of a native prairie mix (hereafter referred to as prairie green roof), (12) extensive green roof consisting of herbaceous perennials and grasses (hereafter referred to as ornamental green roof) and (13) extensive green roof consisting of vegetable and

Table 5.3. Initial physical and chemical properties of green roof substrate.

Component	Unit
Total Sand (%)	86
Extremely coarse sand (>2 mm) (%)	52.02
Very coarse sand (1-2 mm) (%)*	11.33
Coarse sand (0.5 -1 mm) (%)*	8.94
Medium sand (0.25-0.5 mm) (%)*	0
Fine sand (0.10-0.25 mm) (%)*	8.32
Very find sand (0.07-0.10 mm) (%)*	0
Extremely fine sand (< 0.07 mm) (%)*	5.37
Silt (%)	11
Clay (%)	3
Bulk density (g/cm^3)	1.20
Pore space (%)	18.97
Air filled porosity (%)	21.33
Water holding capacity at 0.01 MPa (%)	15.86
pH	7.2
Conductivity (EC) (m mho/cm)	1.59
Nitrate (mg/kg)	65
Phosphorus (mg/kg)	4.5
Potassium (mg/kg)	71
Calcium (mg/kg)	793
Magnesium (mg/kg)	95
Sodium (mg/kg)	65
Sulfur (mg/kg)	94
Boron (mg/kg)	0.7
Iron (mg/kg)	24
Magnesium (mg/kg)	5.2
Zinc (mg/kg)	4.3
Copper (mg/kg)	0.6

Analysis per A&L Great Lakes Laboratories, Inc., Ft. Wayne, IN.
* Analysis per Renewed Earth, Inc., Kalamazoo, MI.

herb plants (hereafter referred to as vegetable green roof), were also replicated on green roof platforms. The green roof platforms were constructed as per VanWoert et al. (2005). The green roof platform plots consist of a previously installed XeroFlor XF-105 drainage layer (XeroFlor

America, Durham, NC) and 10.5 cm of Green roof substrate (Renewed Earth, Kalamazoo, MI) (Table 5.3) installed on June 10, 2009.

The extensive green roofs, prairie green roofs, and ornamental green roofs were watered three times daily for 15 min using overhead sprinklers throughout the 2009 growing season and once daily for 15 min using micro-emitters throughout the 2010 and 2011 growing seasons (Table 5.2). The vegetable green roofs were fertilized in the same manner as the ground plots (Table 5.2) and were irrigated three times daily for 15 min using overhead sprinklers throughout the 2009 growing season and three times daily for 5 min using micro-emitters throughout the 2010 and 2011 growing seasons (Table 5.2). Lesco Professional Landscape and Ornamental All-Purpose Fertilizer 14-14-14 (Table 5.1)(Lesco, INC, Cleveland, OH) was applied to all vegetable green roof plots at a rate of 25 g/m^2 once in 2009, and twice in 2010 and 2011 (Table 5.2).

Plant Selection. Kentucky bluegrass was installed as sod on July 30, 2009. The native prairie mix ground plots and prairie green roofs were sown from seed on May 30, 2009 and May 16, 2009 respectively. Each plot or platform was hand broadcast with 9.1 g of seed containing by weight 0.5% *Achillea millefolium* (yarrow), 2% *Asclepias tuberosa* (butterflyweed), 1% *Asclepias syriaca* (common milkweed), 4% *Aster novae-angliae* (New England aster), 0.5 % *Aster pilosus* (hairy aster), 3% *Coreopsis lanceolata* (sand tickseed), 1% *Desmodium canadense* (showy tick trefoil), 2% *Echinacea purpurea* (purple coneflower), 0.5% *Kuhnia eupatoroides* (false boneset), 2% *Lunpinus perennis* (wild lupine), 4% *Monarda fistulosa* (burgamot), 0.5% *Oenothera biennis* (common evening primrose), 2% *Penstemon digitalis* (foxglove beardtongue), 4% *Ratibida pinnata* (grayheaded coneflower), 6% *Rudbeckia hirta* (blackeyed Susan), 1% *Rudbeckia triloba* (three-lobed coneflower), 1% *Silphium integrifolium* (rosinweed), 1% *Silphium laciniatum* (compass plant), 4% *Solidago rigida* (stiff goldenrod), 3% *Solidago* *speciosa* (showy goldenrod), 2% *Verbena stricta* (hoary vervain), 12% *Andropogon gerardii* (big bluestem), 6% *Elymus canadensis* (Canada wild rye), 5% *Panicum virgatum* (switch grass), 20% *Schizachyrium scoparium* (little bluestem), and 12% *Sorghastrum nutans* (Indian grass). The succulent rock garden and prairie mix ground plots were covered with straw after seeding to provide shade through establishment and the extensive green roof platforms and prairie green roof platforms were covered with shade cloth until germination.

The succulent rock gardens and *Sedum* green roofs were sown from seed with four *Sedum* species: *S. acre, S. album, S. kamschaticum*, and *S. spurium* on May 30, 2009 and May 16, 2009 respectively. These species were planted by mixing 1.2 g of seed with 400 mL of sand and broadcast the mix over each plot or platform by hand. The *Sedum* species selected are common green roof species which have previously been examined for carbon content and carbon sequestration potential on an individual basis by Getter et al. (2009).

Woody ground cover plots were planted from 50 cell plugs (110.90 mL (3.75 fl oz) per cell) of *Vinca minor* on August 7, 2009. Herbaceous perennials and grasses ground plots and ornamental green roofs were each planted with one *Miscanthus sinensis* 'Silver Arrow', two *Perovskia atriplicifolia* 'Little Spire' ('Little Spire' Russian sage), and five *Echinacea puprpurea* 'Magnus' ('Magnus' purple cone flower), five *Hemerocallis 'Mary's Gold'* (' Mary's gold daylily), and five *Rudbeckia speciosa* 'Viette's Little Suzy' ('Little Suzy' dwarf orange coneflower) from 2.5 L (2.6 qt) pots in a uniform pattern on August 7, 2009. Due to poor overwintering of *M. sinensis* that area of the plots was planted with eight *Allium cernuum* and eight *A. senescens* on May 16, 2010.

Deciduous shrub ground plots were each planted with three *Spirea media* 'Snow Storm' (Snow Storm™ spirea), one *Physocarpus opulifolius* 'Summer Wine' (summer wine common ninebark), and one *Weigela florida* 'Wine and Roses' (Wine and Roses® weigela) on August 25, 2009. The broad-leaf evergreen ground plots were each planted from with six *Buxus sempervirens* 'Green Velvet' (green velvet boxwood) and the narrow-leaf evergreen ground plots were each planted with two *Pinus mugho* (Mugo Pine), two *Juniperus chinensis* ' Sea Green' (sea green Chinese juniper) and two *Taxus* x *media* 'Densiformis' (dense spreading yew) on October 26, 2009. All three of the shrub types were planted from 11.35-L (3-gal) containers. Pine bark mulch was spread on the deciduous shrub, broad-leaf evergreen, and narrow leaf evergreen ground plots to a depth of 7.62 cm (3 in) and the herbaceous perennial and grasses ground plots to a depth of 3.81 cm (1.5 in) on May 28, 2010 and the ornamental green roofs to a depth of 2.54 cm (1 in) on June 29, 2010. Mulch was included in the study as many ornamental landscapes incorporate mulch for aesthetics and weed control.

The vegetable ground plots and vegetable green roofs were each planted with two plants each of *Lycopersicon esculentum* (Roma (VF) tomatoes), *Phaseolus vulgaris* (early contender bush beans), *Cucumis sativus* (bush pickle hybrid cucumbers), *Capsicum annuum* (Sweetheart® hybrid sweet peppers), *Ocimum basilicum* (large-leaf Italian basil) , and *Allium schoenoprasum* (chives) (Gurney's Seed and Nursery Co., Scarlet Tanager LLC., Greendale, IN). These vegetable and herb species were selected because of their availability, growth habit (determinate or bush variety), and common use in home gardens. Plugs were grown from seed in 48-cell plug trays (120 mL (4.06 fl oz) per cell) and grown outside, in East Lansing, MI, until transplanting into the ground and green roof plots (Table 5.2). *Capsicum annuum* either did not fruit or did not germinate in all three years, and were replaced in 2011 with *C. annuum* (Budapest hot banana peppers) (Seedway, Hall, NY). These were sown from seed into 98-cell plug trays on April 6, 2011 and grown in a greenhouse until May 24, 2011, then transferred to a lath house at the HTRC until planting in the ground and platforms (Table 5.2).

Data collection and analysis. Soil and substrate samples collected prior to planting between July 7 and 22, 2009 were analyzed to determine initial carbon content of the soil and green roof substrate. Initial soil samples for the vegetable and herb gardens were collected prior to planting in May 2010. Carbon content analysis was performed on above-ground biomass, below-ground biomass (roots), and soil and substrate collected at the end of the growing seasons in 2010 and 2011. Samples were collected on August 31 and September 21, 2010, and August 30, September 12, and September 20, 2011. Plots were divided quarters and each quarter was subdivided into 16 squares. One each sampling date, four subsamples were taken from each plot, one from each quarter, and the subsamples were combined. Only two subsamples were taken from each vegetable and herb garden and vegetable green roof plot because of their smaller size. Sampling locations were randomly selected and recorded so that no square was sampled more than once.

Initial soil samples were collected at depths of 0 to 10.2 cm and 10.2 to 20.4 cm using a 7.6 cm diameter soil corer. Subsequent sampling was based on the methods described in Getter et al. (2009). Above-ground biomass inside a 7.6 cm (3 in) ring, excluding shrubs, was cropped even with the soil or substrate, placed in paper bags, weighed, dried 60˚C for 1 wk, weighed again, and ground in a Wiley mill using a 60-mesh stainless steel screen. Samples were then pulverized on a roller mill, placed in glass vials and stored in a desiccator until analysis of total carbon concentration using a Carlo Erba NA1500 Series 2 N/C/S analyzer (CE Instruments, Milan, Italy). Above-ground biomass in the herbaceous perennial and grasses, deciduous, broad-leaf evergreen, and narrow-leaf evergreen shrubs, and ornamental green roofs was estimated based on plant volume and a model (Miller, 2012). Plant volume measurements were taken on October 21 and November 4, 2010, and October 24 and 30 and November 1, 2011. Above-ground biomass of the vegetable plots was measured after the time of the last harvest (Table 5.2). Plants were weighed, dried at 60°C, and weighed again. Carbon accumulation was calculated by multiplying dry matter weight by total carbon concentration found in the literature.

After the removal of above-ground biomass, all below-ground biomass and soil carbon content were collected from a 7.62 cm diameter, 10.2 cm (4 in) deep soil core, which was removed and stored in plastic bags, weighed in the bag, and separated using a 4.0 mm sieve. Gravel remaining on the sieve was weighed. All root material was removed from the retained and sieved matter using forceps. Root material was rinsed with deionized water, cleaned with a phosphate-free dilute detergent, rinsed with deionized water, and soaked in a 0.01 mol/L NaEDTA solution for 5 min. Cleaned roots were dried at 60˚C for 2 d in paper bags, weighed, ground and analyzed for total carbon content as previously described.

Remaining sieved soil was mixed, placed in a small paper bag, weighed, dried at 60˚C for 2 d, and weighed again. Soil moisture content was calculated by subtracting the dried soil and bag weight from the original weight. Bulk density was also calculated by dividing the original soil sample weight, corrected for moisture content and root and gravel weight, by the volume of the collected soil (ring surface area times the depth of the sample, 463 cm^3). A 25 g portion of each sample was then pulverized and analyzed for total carbon content as previously described. Data on ambient weather conditions were taken from the Michigan Automated Weather Network (MAWN) station East Lansing/MSUHORT located at the HTRC adjacent to the platforms and ground plots.

Mean carbon content was analyzed using ANOVA model in which landscape type and year were fixed effects. Normality issues were resolved using a logarithmic transformation for above-ground biomass, below-ground biomass, soil and substrate, and total carbon content. Influence diagnostics were used to identify outliers, which were removed if they were deemed unrepresentative. The least significant differences (LSD) method of multiple comparisons was used to determine significant differences between treatment means (PROC MIXED, Version 9.1, SAS Institute, Cary, NC).

Results

Weather. During 2009, maximum ambient air temperatures in May, July and August were lower than the following two growing seasons and similar maximum temperatures were recorded during 2010 and 2011 (Figure 5.1). Minimum ambient air temperatures were also lower in May, September, and October in 2009, than those recorded in 2010 and 2011. Total precipitation was greatest during 2011, however, 2009 experienced more precipitation during June and August than 2010 and 2011 but less in September and July (Figure 5.1). Incoming solar radiation was similar for all three growing seasons with totals for June, July, August and September of 2.24, 2.16, and 2.21 million kJ/m^2 for 2009, 2010, and 2011, respectively.

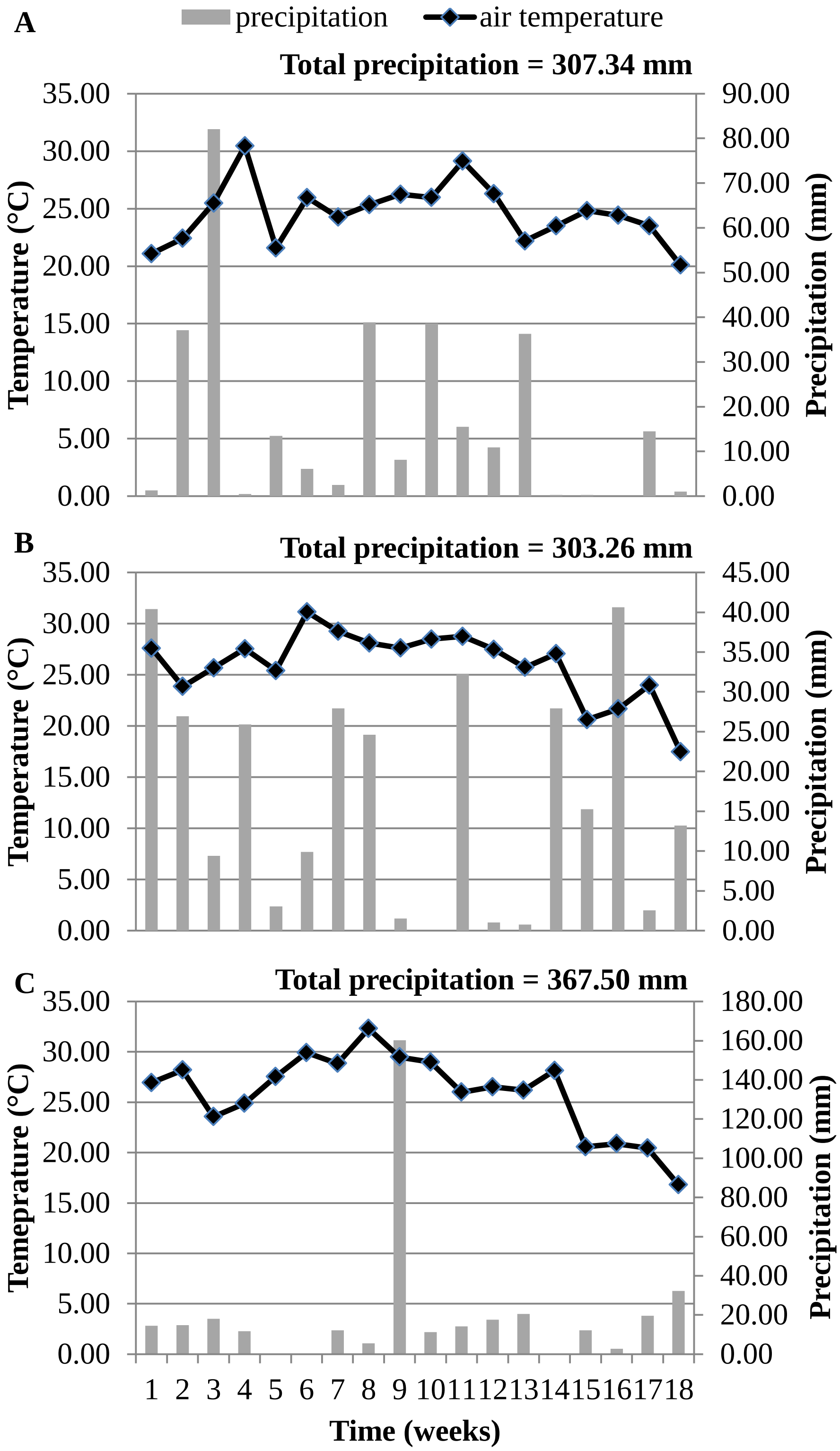

Figure 5.1. Weekly average maximum air temperature in Celsius and weekly total precipitation in mm for the growing seasons of (A) 2009 (May 31-Oct 2) (B) 2010 (May 25-Oct 2) and (C) 2011 (May 29-Oct 1).

Above ground biomass. All results for above-ground carbon content are presented in Table 5.4. The three shrub landscape systems, the herbaceous perennials and grasses and ornamental green roof had the highest amount of carbon in above ground biomass in both years followed by the native prairie mix. The vegetable and herb garden and vegetable green roofs had the lowest amount of carbon in above-ground biomass. For the remaining landscape systems, the prairie green roof was more like the succulent rock garden and *Sedum* green roof than the in-ground native prairie mix. The prairie green roof was the only green roof landscape system to have lower above-ground carbon content than its in-ground counterpart. The only two landscape systems to show an increase in above ground biomass between 2010 and 2011 were the succulent rock garden and *Sedum* green roofs.

Table 5.4. Carbon content (kg/m^2) of above ground biomass of all landscape systems at the end of the 2010 and 2011 growing seasons.

Landscape system	2010	2011
In Ground		
Broad leaf evergreen shrubs	58.61* Aa	65.27 Aa
Deciduous shrubs	52.91 Aa	52.89 Aa
Herbaceous perennials and grasses	61.33* Aa	55.59 Aa
Kentucky blue grass lawn	1.33 Acde	2.69 Acd
Native prairie mix	15.30 Ab	15.96 Ab
Needle leaf evergreen shrubs	40.42 Aa	66.53 Aa
Succulent rock garden	1.94 Bcd	3.91Ac
Vegetable and herb garden	0.03 Af	0.05 Ae
Woody ground covers	1.12 Ae	1.73 Ad
Green Roof		
Herbaceous perennials and grasses	33.61 Aa	64.42 Aa
Native prairie mix	1.27 Ade	4.16 Ac
Succulent rock garden	2.22 Bc	3.49 Acd
Vegetable and herb garden	0.05 Af	0.05 Ae

Means represent 4 observations. *Means represent 3 observations. Means were separated using LSD with an alpha of 0.05. Capital letters denote differences in rows between years within each treatment and lower case letters denote differences in columns among treatments for the transformed data.

Below ground biomass. All the results for below-ground carbon content of the root systems are presented in Table 5.5. Below-ground carbon of the Kentucky bluegrass lawn was higher than any other landscape system in 2010 and higher than all but the vegetable and herb garden in 2011. Broad-leaf evergreen shrubs, deciduous shrubs and the ornamental green roof had the lowest three below-ground carbon amounts during both growing seasons. For the landscape systems in between, herbaceous perennials and grassed and vegetable and herb garden fell in the upper half of the middle during both years. The ornamental green roof was the only green roof landscape system to have lower below-ground carbon content than its in-ground counterpart. The deciduous shrub landscape system was the only landscape system to exhibit lower below-ground carbon in 2010 than in 2011.

Table 5.5. Carbon content (kg/m^2) of below ground biomass of all landscape systems at the end of the 2010 and 2011 growing seasons.

Landscape system	2010	2011
In Ground		
Broad leaf evergreen shrubs	0.08 Af	0.10 Ag
Deciduous shrubs	0.04 Bf	0.14 Afg
Herbaceous perennials and grasses	0.96 Ab	0.58 Abcd
Kentucky blue grass lawn	3.52 Aa	3.25 Aa
Native prairie mix	0.96 Abc	0.32** Adefg
Needle leaf evergreen shrubs	0.27 Ade	0.55 Abcd
Succulent rock garden	0.59 Abcde	0.44 Acde
Vegetable and herb garden	0.83 Abcd	1.42* Aab
Woody ground covers	0.96* Abcd	0.32 Adef
Green Roof		
Herbaceous perennials and grasses	0.19 Ae	0.18 Aefg
Native prairie mix	0.34 Acde	0.72 Abcd
Succulent rock garden	0.30 Acde	0.47 Abcd
Vegetable and herb garden	N/A	0.79 bc

Means represent 4 observations. *Means represent 3 observations. ** Means represent 2 observations. Means were separated using LSD with an alpha of 0.05. Capital letters denote differences in rows between years within each treatment and lower case letters denote differences in columns among treatments for the transformed data.

Soil/substrate. The treatment-year interaction and year had no effect on soil or substrate carbon content (F = 1.30, p = 0.130, α = 0.05 and F = 1.77, p = 0.174, α = 0.05, respectively). All results for soil carbon content are presented in Table 5.6. The vegetable and herb garden had the highest soil carbon content of any landscape system. This was followed by the three shrub landscape systems, herbaceous perennials and grasses and native prairie mix which did not differ from each other. The *Sedum*, prairie, and ornamental green roofs had the lowest carbon substrate carbon contents of any landscape system. All green roof landscape systems had lower substrate carbon content than their in-ground counterpart landscapes.

Table 5.6. Carbon content of soil or substrate of all landscape systems at the beginning of the 2009 growing season and the end of the 2010 and 2011 growing seasons.

Landscape system	**Carbon content (kg/m^2)**
In Ground	
Broad leaf evergreen shrubs	13.41 b
Deciduous shrubs	12.92 bc
Herbaceous perennials and grasses	12.24 bc
Kentucky blue grass lawn	10.11 e
Native prairie mix	12.94 bc
Needle leaf evergreen shrubs	12.41 bc
Succulent rock garden	10.28 de
Vegetable and herb garden	43.47 a
Woody ground covers	11.69 cd
Green Roof	
Herbaceous perennials and grasses	3.27 f
Native prairie mix	3.13 f
Succulent rock garden	3.22 f
Vegetable and herb garden	9.82 e

Means represent 12 observations. Means were separated using LSD with an alpha of 0.05. Letters denote differences among treatments for the transformed data.

Total carbon content. All results for total carbon content are presented in Table 5.7. The three shrub landscape systems and herbaceous perennial and grasses have the highest total carbon contents in 2010. In 2011 they are among the highest, but the ornamental landscape system has similar total carbon content. The *Sedum* green roof and prairie green roof have the lowest total carbon content during both years, much lower than the corresponding succulent rock garden and native prairie mix in-ground landscape systems. The prairie green roof and ornamental green roof were the only two landscape systems to exhibit an increase in total carbon content between 2010 and 2011.

Table 5.7. Total carbon content (kg/m^2) of all landscape systems at the end of the 2010 and 2011 growing seasons.

Landscape system	2010	2011
In Ground		
Broad leaf evergreen shrubs	67.89 Aa	78.75 Aa
Deciduous shrubs	66.38 Aa	65.67 Aab
Herbaceous perennials and grasses	75.10 Aa	68.75 Aab
Kentucky blue grass lawn	14.99 Ac	15.82 Ad
Native prairie mix	30.63 Ab	28.57 Ac
Needle leaf evergreen shrubs	60.73* Aa	62.91 Aab
Succulent rock garden	13.33 Ac	12.30 Ad
Vegetable and herb garden	39.29 Ab	54.18 Ab
Woody ground covers	15.40 Ac	13.43 Ad
Green Roof		
Herbaceous perennials and grasses	37.38 Bb	67.70 Aab
Native prairie mix	4.63 Bd	8.09 Ae
Succulent rock garden	5.87 Ad	7.12 Ae
Vegetable and herb garden	N/A	11.03 d

Means represent 4 observations. *Means represent 3 observations. Means were separated using LSD with an alpha of 0.05. Capital letters denote differences in rows between years within each treatment and lower case letters denote differences in columns among treatments for the transformed data.

Discussion

Carbon content. Overall the three shrub landscape systems, the herbaceous perennial and grasses, ornamental green roof, and native prairie mix landscape systems contained more carbon than other landscape systems examined in this study (Tables 5.4, 5.6 and 5.7). The three shrub landscapes were made up of more woody structures than other landscape systems and woody structures have been shown to contain more carbon than other plant structures (Fang et al., 2007). The herbaceous perennials and grasses, ornamental green roof, and native prairie mix landscape systems contained higher volumes of plant biomass than many of the other landscape systems, which could account for their high carbon contents. The three shrub landscape systems and herbaceous perennial and grasses were also mulched, which reduced weed pressure, reduced the need to weed the plots and disturb the soil, and the breakdown of mulch over time may have contributed to soil carbon content.

Broad-leaf evergreen shrubs, deciduous shrubs, and the ornamental green roof landscape systems did, however, have the lowest below-ground carbon contents during both growing seasons (Table 5.5), contrasting with their high above-ground biomass, soil/substrate, and total carbon contents. Below-ground carbon contents for these and the narrow-leaf evergreen landscape systems were estimated based on above-ground biomass volume based on information from Miller (2002), which may have resulted in underestimation of below-ground biomass. Interestingly, the Kentucky bluegrass lawn had the highest below-ground carbon content and was likely caused by the very dense root systems formed by this landscape system.

In many cases the green roof landscape systems contained less carbon than their corresponding in-ground landscape systems. The lower above-ground biomass of the prairie green roof may have had a number of causes. Full coverage of the plots was not achieved, unlike the in-ground native prairie mix plots and less colonization by weed species in the green roof platforms than the in-ground plots may have increased the amount of time it would take to achieve full coverage. Shallower substrate may have inhibited root growth, which would have reduced the size of plant the plots could support, limiting plant above-ground biomass volume. The nature of the green roof substrate, which has good drainage, may have enabled more substrate carbon to leave landscape systems than what leached out of the soil of the in-ground landscape systems.

Only six landscape systems showed an increase in carbon content between 2010 and 2011. These were succulent rock garden and *Sedum* green roof for above-ground biomass carbon content (Table 5.4), deciduous shrubs and vegetable and herb garden for below-ground biomass carbon content (Table 5.5), and prairie green roof and ornamental green roof for total carbon content (Table 5.7). The succulent rock garden and *Sedum* green roof and prairie green roof took longer than other landscape systems to achieve the desired coverage of plot area, which may explain the differences between the two years for those landscape systems. Many of the other landscape systems contained either slow growing plants (the two evergreen shrub plots) or plants that experienced winter dieback followed by regrowth, resulting in little difference in biomass between the two growing seasons. The vegetable and herb garden experienced more weed pressure in 2011 and inclusion of weed roots in the sampling may have inflated the below ground carbon content of this landscape system.

Implications. All of the green roof platform landscape systems exhibited greater carbon sequestration than that reported by Getter et al. (2009). After adjusting for initial substrate carbon content (3.15 kg C/m^2) the *Sedum*, prairie and ornamental green roofs contained 4.67, 5.64, and 65.25 kg C/m^2, respectively after the third growing season compared to .37 kg C/m^2 (Getter et al., 2009). For the prairie and ornamental green roofs this is not surprising as the species represented in those landscape systems have much greater above-ground biomass and more woody structures than the *Sedum spp.* examined by Getter et al. (2009). Getter et al. (2009) also only examined above- and below-ground biomass and substrate carbon content for single species of *Sedum* in a substrate only 6 cm deep. This suggests that green roofs with deeper substrates are capable of greater carbon sequestration. In other landscape systems, greater species diversity can lead to greater carbon sequestration (Rhodes, et al., 2000; Tilman et al., 2006). This may be the case in green roofs as well, but when Getter et al. (2009) examined existing green roofs with mixes of *Sedum* species, their results were consistent between studies. Another possible explanation for the discrepancy between the Getter et al. (2009) studies and this one is that all of the roofs that they examined were not irrigated. The irrigation supplied by this study may have enabled greater growth of the *Sedums*.

Getter et al. (2009) also examined the carbon budget of a green roof and reported that the materials needed to install the type of green roof used in that study had an embodied energy of 6.5 kg C/m^2 with a payback period due to energy savings of about .70 kg C/m^2 of 9 yrs. When the carbon sequestered by the green roof vegetation was included it reduced that payback period by 2 yrs (Getter et al., 2009). Based on those calculations, assuming a similar embodied carbon for the substrate used, roofs with a 10.2 cm depth would contain 10.5 kg C/m^2 with a payback period of 15 yrs assuming similar energy savings. For this study the *Sedum* and prairie green roofs examined in this study reduce the carbon payback period to 2.2 and 1.9 yrs, respectively. The vegetable and ornamental green roofs reduced the payback period even further to 1.2 and 0.2 yrs, respectively.

The carbon contents of the in-ground landscape systems indicate that there may be a great deal of potential for carbon sequestration in ornamental landscapes. Marble et al. (2011) stated that approximately 200,000 ha of land in the U.S. are devoted to nursery production. Assuming that a similar amount of land is in ornamental landscapes, excluding urban forests, that land could store between 0.25 and 1.59 Pg C based on landscapes examined in this study with the lowest and highest total carbon content (Table 5.7). The total carbon content of landscape systems examined in this study also fall within the range of some reported values for forests in the United States, which range between 15.18 and 72.12 kg C/m^2 (Smith et al., 2004).

There are however some important questions that need to be asked about the quality and permanence of that carbon storage. Nowak et al. (2002) reported that management practices had a large impact on the ability of urban forests and trees to sequester carbon and that more intensive management with powered machinery and tools reduced the net amount of carbon sequestered. The same would be the case in ornamental landscapes. The Kentucky bluegrass lawn in this study was mowed as needed at least three times a growing season with a gasoline powered mower, resulting in carbon emissions. Many lawns are mowed much more frequently than that, some as often as once a week, which would result in even more carbon emissions, which would erode away at the already small amount of total carbon sequestered by that landscape type (Table 5.5). Many landscapers also manicure shrubs, which was not done for this study, and would also result in emissions that would reduce the net carbon sequestered. Management practices, or rather the change of management practices as land changes hands has been a barrier to small forests entering the carbon exchange (Bigsby, 2009). This may also be the case of ornamental landscapes, for which management may differ depending on not only ownership, but the landscapers in charge of managing the land.

Management and ownership changes in ornamental landscapes can also mean the complete removal of plant material in the landscape, which raises another issue to consider: the fate of removed material. In many landscape systems dead material is removed and either chipped, burned or put in a landfill. Nowak et al. (2002) has suggested that in the case of urban trees, when a tree is replaced and mulched its replacement will not sequester any more carbon than is emitted by the decomposing mulch, generating a cap on how much carbon a landscape will contain before it reaches equilibrium. The same is likely true of ornamental landscapes. Herbaceous perennials and grasses are often cut back on an annual basis to remove unsightly dead materials. We performed this maintenance for the herbaceous perennial and grasses, vegetable and herb garden, ornamental green roof and vegetable green roof landscape systems, but were unable to monitor the removed carbon. Nor could we account for carbon released when the native prairie mix and prairie green roof landscape systems died back during the winter. Once this is taken into account it could be that net carbon sequestration for these landscape systems is lower than this study would suggest. More research should be done to determine how changes in ownership and management of ornamental landscape systems and the fate of removed materials affect both the quantity of carbon sequestered and its permanence. Without this information it will be difficult to move forward in including ornamental landscapes in carbon trading programs.

Conclusions

Results of this study suggest that ornamental landscapes both in-ground and on green roofs have the ability to sequester carbon. The landscape systems that were able to sequester the most carbon contained higher amounts of woody plant structures and higher plant biomass volumes, such as the three shrub landscape systems and the herbaceous perennial and grasses, native prairie mix, and ornamental green roof landscape systems. Two of the green roof landscape systems examined, *Sedum* and prairie green roofs, did not sequester as much carbon as their counterpart in-ground landscape systems. This was likely due to differences in soil and substrate properties and the ability the landscape systems to reach 100% surface coverage. Even so the green roof landscape systems sequestered more carbon than shown by previous research and their use may reduce the payback period of carbon embodied in the green roof materials from 15 yrs to less than 3 yrs. Although this may be promising for the green roof industry, greater carbon sequestration can still be achieved on the ground and carbon sequestration will likely only be a secondary benefit of green roofs. The in-ground landscape systems also show promise for contributions to carbon sequestration and possibly carbon trading, with total carbon values similar to some reported in the literature for forests in the United States.

The types of landscape systems examined also raised some questions about how maintenance would affect net carbon sequestration. Research could be done to address the questions of how management practices and the tools used in landscaping affect carbon emissions and therefore net carbon sequestration and how the removal of materials from the landscape changes the permanence of the carbon sequestered and the time frame in which the landscape will reach carbon equilibrium.

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