

Review

Sustainability of Urban Agriculture: Vegetable Production on Green Roofs

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Abstract: The practice of producing vegetables on green roofs has been gaining momentum in recent years as a method to facilitate agricultural sustainability in urban areas. Rooftop gardens are becoming an important part of the recent rejuvenation of urban agriculture, and offers alternative spaces to grow vegetable products for urban markets. Green roofs create spaces for the production of vegetable crops, which then generate opportunities for integrating agriculture into urban communities. However, vegetable production activities on rooftops are currently minimal due to multiple challenges that must be overcome before widespread implementation will occur, and these are presented and discussed herein in great detail. Although intensive green roof systems (>15 cm medium depths) are thought to be most suited for vegetable production, the greatest potential for sustained productivity is probably through extensive systems (<15 cm depths) due to weight load restrictions for most buildings. Thus, shallow-rooted vegetables that include important salad greens crops are thought to be the most suited for extensive systems as they can have high productivity with minimal inputs. Research presented herein agree that crops such as lettuce, kale and radish can be produced effectively in an extensive green roof medium with sufficient nutrient and moisture inputs. Other research has indicated that deeper-root crops like tomato can be produced but they will require constant monitoring of fertility and moisture levels. Vegetable production is a definite possibility in urban areas on retrofitted green roofs using minimal growing substrate depths with intensive seasonal maintenance. Rooftop agriculture can improve various ecosystem services, enrich urban biodiversity and reduce food insecurity. Food production provided by green roofs can help support and sustain food for urban communities, as well as provide a unique opportunity to effectively grow food in spaces that are typically unused. The utilization of alternative agricultural production systems, such as green roof technologies, will increase in importance as human populations become more urbanized and urban consumers become more interested in local foods for their families. Although cultivation of food on buildings is a key component to making cities more sustainable and habitable, green roofs are not the total solution to provide food security to cities. They should be viewed more as a supplement to other sources of food production in urban areas.

Keywords: extensive green roofs; rooftop gardens; sustainable agriculture; urban food security

1. Introduction

1.1. Green Roofs and Urban Agriculture

The practice of producing vegetables on green roofs has been gaining momentum in recent years as a method to facilitate agricultural sustainability in urban areas. Rooftop agriculture allows urban areas to become more sustainable in their resource utilization, and to assist the development of food security for local residents. Rooftop gardens are becoming an important part of the recent rejuvenation

of urban agriculture, and offers alternative spaces to grow vegetable products for urban markets [1]. The production of vegetables on rooftops should not be thought of as a replacement for large-scale vegetable production in rural areas [2], but rather as an enhancement to the urban food movement by providing another source of local, fresh, foods [3]. Many urban areas are now producing over 20% of their vegetable needs from within city boundaries [4], but due to limited growing spaces, land for crop production is often the most limiting factor to urban food production systems. Urban farms can produce significantly more produce on a per acre basis than that typically produced in rural areas, due to the intensive, focused small-scale farming techniques utilized for limited spaces.

Urban agriculture is becoming more common in many cities as consumers seek healthy, local produce. Local food production can reduce carbon dioxide emissions by having minimal, short-distance-transportation from where food is produced to where it is consumed, and can also help consumers to become better educated about vegetable crops and their production cycles through programs at local farms. Urban agriculture is widely utilized in developing countries, although some cities in developed countries worldwide strive to source at least a portion of their food requirements locally. Numerous efforts to expand urban food production are underway in many cities, and combined with mounting interest in local food systems, should provide the incentive needed to drive long-term urban food production strategies [4]. The contributions of urban agricultural activities to local food supplies is now significant in several cities, including Bologna (Italy), Chicago (USA), Cleveland (USA), Hong Kong (China), Montreal (Canada), New York (USA), Portland (USA), Seattle (USA), Shanghai (China), Taipei (Taiwan), Tokyo (Japan), Toronto (Canada), and Vancouver (Canada) to name a few. Cities, such as these, are interested in providing sustainable, local and fresh food to residents, which is not an easy task, and depends on several factors including available land parcels to grow produce, farm size, revenue generation potential, postharvest handling, and distribution methods [4]. For urban agriculture to be most successful, there is a need to increase vegetable crop cultivation within city boundaries. However, land that has traditionally been used for agricultural purposes within urban areas, such as vacant lots, is vulnerable to potential development. Thus, urban agriculture is challenged by the lack of available space in cities to meet current demands for locally produced foods. Green roofs can be used in this capacity to effectively replace green space lost during building construction. Therefore, rooftop agriculture (particularly green roof production systems) has become an attractive possibility to increase localized urban agriculture [1].

Green roofs can potentially play an important role in urban farming and provide great benefits to urban residents. Green roofs offer an alternative growing space to provide fresh vegetable products to urban markets. Vegetable crops grown on rooftops provide numerous ecological and economic benefits in addition to being a source of locally produced fresh food for city inhabitants [5], including storm water management, energy conservation, mitigation of the urban heat island effect, increased longevity of roofing membranes, and providing a more aesthetically pleasing environment in which to work and live [6]. Although there is great potential for using rooftops to grow vegetables in urban areas, there are several obstacles that must be overcome before this production system can be more widely used; these issues include installation and maintenance costs, roof weight limitations, media composition and depth, cultural practices, potential water-quality issues of effluent runoff, and influence of crop production on other well-known benefits attributed to green roofs [7]. Despite these possible setbacks from incorporating green roof technology into urban agriculture, the utilization of all available plant growing spaces in and near cities will most likely be required for future generations to sustain food security in urban areas.

Some cities are known for their commitment in creating green roof spaces on buildings within city boundaries. Moreover, many cities have legislation, policies, and tax incentives that either encourage or mandate green roof systems on new building developments. For example, Toronto, Canada has green roof by-laws that require all new developments above 200 m² to include a green roof covering 20–60% of the total roof area. The Green Permit Program in Chicago, Illinois, USA encourages developers to incorporate environmentally sensible designs like green roofs on new

buildings. As of 2014, these incentives have contributed to Chicago having 516,951 m² of green roof coverage [8]. The value of incentive programs for developing green roofs on city buildings is to increase the development of eco-friendly environments, contribute to improve their overall appearance, and increase the environmental health of cities [9].

1.2. Potential Benefits of Green Roofs

Green roofs are a constructed vegetated roof system that can provide numerous environmental benefits to the surrounding ecosystem. They aid in storm water management, increase the longevity of roofs, create habitats that support biodiversity in urban settings, provide building insulation that reduce cooling and heating costs, and in addition, can create green spaces for human enjoyment [9]. Probably the greatest single environmental benefit provided by green roofs is the reduction in total amounts of storm water runoff [6], as green roofs can reduce runoff as much as 60 to 100%, depending on the type of green roof system [10]. However, besides the numerous associated environmental benefits, green roofs can also provide social and learning experiences for local residents.

Green roofs can be a resource to enrich urban education and experiences. Many children have no connection to farming or interactions with outdoor spaces when growing up in an urban environment. They do not gain experiences or have an awareness to visualize how food is produced, such as picking tomatoes from a plant or watching lettuce grow. This emphasizes the role that a green roof on a school or community center could play. For example, the East Campus of the Ogden International School of Chicago was built in 2011 primarily as an elementary school, but also functions as a community space for the neighborhood and has a functional green roof used for educational purposes. Thus, although green roofs are primarily installed for their environmental benefits, they can also have educational value for the surrounding communities.

Food production can also be an associated benefit of green roofs. Although rooftop agriculture is gaining momentum and rapidly developing to become an important part of urban agriculture, the overall implementation of growing food on green roofs is limited by many different factors including lack of suitable space on rooftops for growing vegetable crops and building regulations (e.g., weight loads) that prevent food production on roofs [11]. Many large rooftops on abandoned apartment buildings, school buildings, industrial buildings, shopping malls, or gymnasiums, can be potential sites for urban farms. As more humans populate urban areas, additional areas to produce food, such as rooftops will be required to supply food for this growing populace.

1.3. Green Roof Structure and Types

Green roofs are structures that consist of a number of component layers. These layers include a root barrier to prevent damage to the underlying roof structure, drainage layer to retain a portion of storm water for plant usage yet facilitate the removal of excess water, a filter fabric to prevent the drainage layer from clogging, the growing medium, and lastly vegetation on top [6]. Tray modules that allow easy removal or addition of growing medium and plants, or vegetated mats are often used to reduce installation and/or maintenance as well as costs for many green roofs. Many green roofs are currently designed with plant materials requiring minimal maintenance to reduce expenses.

Although green roofs provide tremendous opportunities to grow vegetables for urban residents, the structural weight constraints of buildings must be taken into consideration prior to planting [1]. The weight constraints of buildings directly determines the specific type of roof, either intensive or extensive, that can be utilized. Intensive green roofs have growing medium depths of more than 15 cm, which allows for the installation of shrubs, trees, paths and various landscape features, such as bench seating [9]. In comparison, extensive green roofs are limited to a shallower depth (<15 cm) of growing medium, with plant selections typically limited to ground covers and smaller growing plants. Intensive green roofs are named due to their typically more intense maintenance requirements. Extensive roofs usually have minimal maintenance associated with them, but due to the more shallow

media depth, plant species are limited to herbs, grasses, mosses, and drought-tolerant succulents, such as *Sedum* [6].

The composition of a green roof medium is an important consideration, as it directly affects roof weight load capacities and water/effluent runoff. The most comprehensive standards for green roof materials and installation are available from the German Landscape Research, Development, and Construction Society, known by the acronym FLL (for Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau), which provides information on appropriate granulometric distribution (particle sizes), organic matter levels, and other properties of mediums that are essential for green roof design and maintenance [12]. In areas with high precipitation, choosing a more porous aggregate such as light-weight aggregate or pumice is important since slower moisture infiltration rates increase weight loads on roofs compared to mediums with faster rates. In these environments, it can be difficult to sustain plant growth due to excess leaching of nutrients. However, when fertilizers are applied to improve plant growth, nutrient leaching and runoff may be a problem, especially if water runoff capture and reuse practices are not utilized in some manner [12].

2. Vegetable Production on Green Roofs

Since many vegetables prefer deeper soil depths, intensive green roofs that provide greater rooting depths have been considered best to maximize their productivity. Many intensive green roof mediums provide high organic matter and nutrient content, which allow for a significant amount of root development and above-ground productivity. Yields of deep rooting vegetables such as tomato (*Solanum lycopersicum*) grown in an intensive green roof were shown to be comparable to those from in-ground conventional agriculture systems [13]. Additionally, other research has also indicated that tomato can effectively be grown in an extensive green roof when adequate fertility and moisture is provided [1]. Besides tomato, the production of bean (*Phaseolus vulgaris*), cucumber (*Cucumis sativus*), pepper (*Capsicum annuum*), basil (*Ocimum basilicum*), and chive (*Allium schoenoprasum*) is possible in an extensive green roof with irrigation and minimal fertilizer inputs [14]. Thus, the use of extensive systems should be more than adequate for shallow-rooted vegetables that include important salad greens crops such as lettuce (*Lactuca sativa*) and kale (*Brassica oleraceae* var. *acephala*). Vegetable production is a definite possibility in urban areas on retrofitted green roofs using minimal growing substrate depths with intensive seasonal maintenance [14]. Rooftop vegetable crop agriculture can be productive on shallow extensive green roofs using standard green roof substrates [13], but maximum productivity in these systems will require high nutrient and irrigation inputs. Although there are several challenges to effectively managing green roof vegetable production systems, they provide a unique opportunity to effectively grow food in spaces that are typically unused [6].

3. Green Roof Management Considerations for Vegetable Crops

For centuries, urban dwellers have cultivated many vegetables, such as lettuce, pepper, cucumber and tomato in rooftop gardens, but there are still several challenges that need to be overcome to maximize vegetable productivity in green roof settings. Although there are many challenges, these can directly relate to benefits for the surrounding human populace and ecosystems. Many of these challenges and suggestions for improvement are outlined in Table 1, which include biodiversity habitat, growing substrate, irrigation efficiency, maintenance activities, nutrient management, pest control, plant materials (vegetable crop and variety selection), pollination systems, and water management.

Table 1. Current challenges for vegetables grown in extensive green roof culture and possible suggestions for improvement.

Challenges	Suggestions for Improvement
Biodiversity/Habitat	Create microhabitats to improve wildlife diversity Improve plant diversity through creation of various microclimates
Growing Substrate	Alternative growing mixes with high moisture and nutrient holding capacities Limited amounts of heavy organic materials, like compost
Irrigation Efficiency	Moisture monitoring for specific crop requirements Water scheduling and adjustment due to rainfall Match water use requirements to crop needs
Maintenance Activities	Monitor crops every few days to determine work activities to complete Harvest crop products as needed to maximize productivity
Nutrient Management	Strategic fertilizer management plan to provide adequate nutrients Decrease nutrient pollutants thorough capture and re-circulation
Pest Control	Minimize transfer or importation of pests to green roof Weed, insect and disease outbreaks can be minimized by early detection Utilization of natural materials to prevent pollutants in water runoff
Plant Materials	Dwarf or determinate vegetable varieties to minimize growth Utilization of plugs or transplants to enhance plant establishment Secure larger plants in some manner from wind damage
Pollination Systems	Position urban environments to align with developed ecosystems Ecosystem health dependent on pollinators built into urban environment
Water Management	Medium constraints to increased water retention Use light-weight organic mulch materials to improve moisture retention and lower soil temperatures

3.1. Biodiversity Habitat

Urban development inevitably destroys habitats, resulting in the loss of biodiversity [11]. Green roofs play an important role in conservation of biodiversity by creating a living space in an urban environment where none had existed before [15]. This reverses the typical thought that concrete urban areas are void of life. Green roofs can create microhabitats to improve wildlife diversity, and the addition of plant diversity creates habitats and supports various types of wildlife including insects, birds and mammals. Although there are limitations in the creation of wildlife habitats in a green roof setting (due to the often times highly stressed environment from lack of moisture and/or high temperatures), careful selection and incorporation of specific individual features can create microclimates so that a suitable habitat can be achieved [15]. For example, a relatively dense and highly diverse plant species collection can be developed on an intensive green roof to generate various microclimates (different layers) creating protected, shady areas and/or more open, sunny sites which will subsequently also support greater wildlife diversity. Microhabitats created for wildlife, such as nesting areas for birds or providing food sources for butterflies, allow for greater diversity to develop in a green roof environment. However, weed establishment should be monitored (from weed seed introduction) to prevent one or a few species from becoming dominant, which can destroy biodiversity and microhabitats [12].

Agricultural activities are well-known to reduce ecosystem biodiversity, but in a limited area like a green roof, the resulting biodiversity can be significantly improved by planting crops compared to a sterile roof environment. Agricultural activities on a green roof will improve the resulting biodiversity that develops in this micro-ecosystem. However, the proper selection of crop plants plays a critical role in creating highly diverse habitats to attract numerous organisms. Crop diversity is critical in the creation of numerous habitats, such as with those crop plants that produce flowers to attract pollinators or high amounts of shade to develop habitats for specific invertebrates. Moreover, many techniques can be used to improve the resulting biodiversity that develops on green roofs used for food production activities, including companion planting, intercropping, composting, and development of pollinator habitats to name a few. Thus, green roofs can improve urban biodiversity, even with ongoing agricultural activities.

3.2. Pollination Systems

Green roofs can provide habitat to many bee species, and the presence of diverse bee communities is crucial to allow natural ecosystems to develop and become sustainable [16]. Pollinators are critical to the biodiversity of green roof vegetable systems due to the pollination services they provide. For many cross-pollinated vegetable crops, such as cucumbers and squash, bee pollination is essential for fruit development and without these pollinators, these vegetables will not set fruit [17]. Additionally, the yield of many vegetable crops would most likely be increased if the green roof is designed to sustain bee populations [16]. Pollinator insects such as various bees, butterflies, moths, and wasps pollinate various vegetable crops. However, pollinating insects depend on flowers, and a diversity of plant species are key to attracting these insects to a green roof environment [12]. A suitable habit to attract native pollinators, must offer adequate sources of food, water, and shelter. Moreover, bees, butterflies, and other pollinators need shelter to hide from predators, protect themselves from inclement weather conditions, and rear their young. Proper nesting sites also promote the colonization of garden areas by pollinating insects. By maintaining natural and cultivated habitats where these insects can nest, rest, and forage, a healthy pollinator population can be established. However, green roofs at high elevations will generally require at least one honeybee colony to assist in pollination services for vegetable crops grown in this environment.

Urban environments are generally extremely detrimental to the natural pollinator ecosystem due to the lack of pollinator plants, which are essential to attract pollinators. A healthy pollinator ecosystem has relatively low requirements to function properly, and can be established in urban areas easily with the proper selection of plants to attract numerous types of pollinators. Although many different vegetable crops can attract different types of pollinators, companion planting of other more ornamental flowering species or herbs is an effective way to improve the pollinator populations. The planting of certain herbs or other flowering plants near vegetable crops on a green roof environment will most likely promote native pollinator activity. The proper selection of plants is of the utmost importance to include those that attract bees and other pollinators, including herbs such as basil, bee balm (*Monarda didyma*), and sage (*Salvia officinalis*) [18]. To ensure that the pollinators will have plant flowers to forage from spring through fall, it is best to select various plants that flower at different times throughout the growing season. The choice of plants that have numerous flower colors, shapes, and sizes will also help attract a much wider assortment of insects with different foraging habits. Furthermore, larger clusters of a plant species are better for attracting pollinators than several smaller clusters in and around the garden space. Thus, green roofs can be positioned to play major roles in urban environments to develop microhabitats to improve pollinator diversity.

3.3. Growing Substrate

Green roof mediums may not contain optimal fertility levels required to maximize vegetable plant growth and productivity, and the success of rooftop vegetable production often depends on fertility management systems to create optimal growing conditions [19]. Due to weight limits often associated with extensive green roofs, soil and organic materials can be too heavy to install as a growing medium. The FLL guidelines stipulate ranges for organic matter in green roof mediums. Soil-less alternative growing mixes that are composed predominately of a light-weight material are often used, such as light-weight aggregate or shale (75% to 90%) mixed with a low percentage of organic materials. Thus, extensive green roof substrates tend to be highly mineral-based with small amounts of added organic matter, often less than 10% [15]. The light-weight material is coarse, inert, and does not provide any nutrients for plant growth. Moreover, the addition of organic materials can provide some nutrients for plant growth, as well as increased nutrient and moisture retention, but will become depleted after a few growing seasons, unless replenished in some manner [12]. Although soil-less, light-weight growing mixes are most commonly used for extensive green roofs, soil-based systems that are often used for intensive green roof cultivation are more environmentally and socially beneficial for urban areas than are soil-less based systems [20].

The composition of a green roof medium directly affects runoff and roof weight load capacities. Mediums with slower infiltration rates will cause greater weight loads to develop on roofs compared to those that have faster infiltration rates as they will have quicker water drainage and runoff. The ideal medium for green roof installations would have unique properties that are typically not found in most mediums, such as being light-weight, with easy installation and high insulation properties, have good aeration and high moisture retention capabilities, do not leach large amounts of soluble solids, and have adequate cation-exchange capacity and fertility for plant growth [5]. Therefore, there is still work to be done in the development of medium materials best suited for extensive green roof vegetable crop culture.

3.4. Water Management

Moisture retention in extensive green roof mediums is an important factor to consider when trying to optimize water holding capacity throughout the growing season. Regardless of the green roof type, a substrate must be included for plants to grow by optimizing water holding capacity, providing nutrients and structure, and minimizing bulk weight without exceeding the overall weight limits. Extensive green roof mediums have an average planting depth of 8 to 15 cm, and consist of a 75% to 90% light-weight aggregate, shale, or other materials, with 10% to 25% organic materials added primarily for water and nutrient retention [12,21]. Extensive green roof mediums are typically a balanced combination of light weight mineral aggregates such as HydRocks[®] light-weight soil media (Big River Industries, Inc., Atlanta, GA, USA) containing calcium clay or a pumice or shale with added organic compounds (Rooflite[®]-certified green roof media, Landenburg, PA, USA), and these types of mediums are more suited for retrofitted roofs or those with low weight restrictions [22]. However, Rooflite[®] agricultural 600, 700, and 800 is marketed as the choice for rooftop farms for the production of vegetable and herbs, but even the lowest weight product exceeds weight limit restrictions for many extensive green roofs (>293 kg/m²).

Due to the lack of organic matter in extensive green roof mediums to prevent weight load constraints on building structures, providing sufficient moisture holding capacities in soils can be a challenge to achieve maximal vegetable crop plant growth. Since these systems require a light-weight medium, only a low percentage of organic matter (such as compost) may be added to maintain a limited weight requirement. Additionally, the light-weight aggregate is coarse, which allows water to drain through the medium quickly, often causing drought conditions soon after watering from the low amount of organic matter in the medium.

Water management plays an important role in the management of vegetables grown in green roof environments [23]. Drought is one of the most limiting factors on extensive green roof systems given shallow medium substrate depths (<15 cm) and reliance on natural precipitation to sustain growth [6]. However, most of the precipitation captured in green roof media or vegetation will eventually evaporate from the soil surface or will be released back to the atmosphere by transpiration [6], and about 45% of all rainfall on green roofs is probably recycled in this manner [23]. Water management is always an important part of vegetable crop culture since most vegetables tend to be inefficient users of soil moisture, and contain anywhere from about 80% to 95% water. A consistent supply of water is essential to maintain plant productivity, and this is even further exacerbated in extensive roof systems due to limited medium depths. To help maintain moisture in the medium and reduce peak temperatures, the use of light mulching materials that do not add significant weight to the roof structure may be at least a partial solution to help with moisture retention and to lower soil temperatures, although preventing material loss from high winds could be a problem in some situations.

3.5. Irrigation Efficiency

Irrigation and water use are an important part of green roof vegetable production systems to maintain proper levels of moisture for plant growth without incurring any loss due to either over- or under-watering. Supplemental irrigation is an essential component of vegetable production systems for extensive green roofs, since adequate and consistent moisture is necessary to maximize produce quality and yield [14]. Green roof systems were initially designed to aid in storm water management, with light-weight mediums developed to allow increased moisture holding capacity and limited plant variation. These green roof systems included a drainage layer that collected excess water into a small reservoir from either rainfall or irrigation, and would also allow overflow if the water holding capacity of that layer is full. Additional water is allowed to run-off to avoid floating or damaging other layers once reservoirs are full. Moreover, the rate of evaporation or utilization of the reserved water depends on numerous factors, such as temperature, wind conditions, and types of plant materials used; and during periods of no rainfall, supplemental irrigation is critical to provide water to plantings, which is especially crucial when integrating vegetables on a green roof due to the typically high stress environments.

In vegetable green roof systems, moisture must be monitored in the growing substrate and matched to a specific crop's water requirements more so than with ornamental plants (such as *Sedum* spp.) to allow their productivity to be maximized. In most situations, more efficient irrigation systems (such as trickle irrigation) is more suitable for green roof vegetable culture compared to less efficient systems (such as overhead irrigation or hand-watering) [12]. To minimize manual irrigation efforts, water schedules can be automated, although the timetable must be adjusted according to changes in rainfall patterns or evapotranspiration rates, which would require either reducing or increasing water scheduling for plants. Moreover, controlling the amount of water supplied through irrigation in relation to water usage by the crop is an important part of vegetable crop green roof systems to avoid either over- or under-watering.

3.6. Maintenance Activities

The continual maintenance required in green roof vegetable production systems is a major impediment to widespread utilization and implementation, as significant maintenance activities are required to keep plants in a highly productive state. This is the main reason that many green roofs use low maintenance plants, such as *Sedum* spp., although the potential benefits in terms of diversity and food production are much greater with vegetable crops. However, vegetable crops require considerable amounts of monitoring to ensure their proper growth and development throughout the growing season. All vegetable crops should be monitored every few days to determine work activities that need to be completed, such as disease or insect control, or hand-weeding. Moreover, crop products that are ready to harvest should be removed as soon as possible to maximize produce freshness, minimize loss from over-ripe or diseased fruit, and to improve productivity of some vegetable crop plantings. These are just a sampling of the activities that are essential to maintain a more vigorous and healthy vegetable planting, which is required for high productivity and yields.

3.7. Pest Control

Although many expect that there are not typically serious vegetable crop pest concerns on an elevated green roof, this is rarely the situation. Pest control is a necessary part of vegetable production on green roofs [5]. We have observed that many types of pests, including numerous diseases, insects, and weeds can become major problems in a green roof planting. Pests can arrive to the green roof in many different ways, such as with plugs or plants, soils or composts, on the bottom of shoes, or by wind. Animals, such as raccoons or squirrels, can also be problematic pests in certain situations. Both of these pests have been devastating to our green roof vegetable research plots during the summer months (which is at tree canopy level), as they have especially eaten or destroyed fruits resulting from

tomato and melon research. In our experiences, nettings and other barriers have had little effect on preventing damage.

Management of pests must be carefully considered, especially if chemical treatments are used, due to potential environmental contamination from runoff or drift. Monitoring, through routine inspections, as well as prevention are the best methods to maintain healthy plants, and are really the best practices to use for pest control [17]. Weed, insect and disease outbreaks can be minimized and often prevented from causing excessive amounts of damage by early detection. However, it can be more challenging with animal pests due to limited options, although natural repellents, such as capsaicin sprays, can be effective in certain situations.

3.8. Nutrient Management

Nutrient management plays a key role in the success of green roof vegetable production systems. Fertility practices are an important part of maximizing vegetable crop productivity in both intensive and extensive green roof systems. Although initial green roof mediums often have sufficient fertility for the first growing season, supplemental fertilization is required in following years, with slow-release fertilizers (such as compost or those that are coated with plastic resin or sulfur polymers which slowly break down) often used to reduce the amount of nitrate and phosphate runoff [12]. Due to the composition of extensive green roof substrate mixes, providing supplemental nutrients is essential to maximize vegetable crop plant growth and productivity [1,13]. However, organic matter, such as compost, should not be repeatedly added each successive year to extensive green roofs, as their added weights can cause the roof weight load limit to be exceeded, compromising the roof structure. Although organic matter will breakdown over time, it will take several years in green roof environments to completely dissipate, due to lower breakdown rates resulting from lower microbial activity in heat- and water-stressed environments compared to typical garden soils. Thus, the added weight of newly added compost with that added from previous years will most likely increase a roof's weight load over time, and often beyond the weight load capacity of the roof.

Compost is a preferred source of an organic amendment for green roof substrates due to its high nutrient content, microbial populations and recycling value [24]. However, nutrient use efficiency from these products is probably low for several reasons, including problems of nutrient leaching and non-plant available forms. The application of nutrients from compost teas may prove over several years to be a useful fertilizer delivery method since it may build green roof soils through increasing soil microbial populations and cation-exchange capacities of plant available nutrients [1,24–26], while keeping building weight constraints at a low level. However, compost teas also have the potential to leach through the medium without providing much nutrient value to plants, and other forms of slow-release fertilizers may be better suited to provide plant available nutrients for crop growth.

Managing substrate fertility is often challenging, since green roof substrates are often engineered with low amounts of organic matter [13], and this provides for high permeability and low cation-exchange capacity [27]. Vegetable yields typically increase with greater fertilizer use, although there is a concern that when high rates are applied to the plant to improve growth, nutrient leaching or runoff may become a problem [28]. High and consistent fertility levels in the growing medium is required during the growing season to produce high yields for most vegetable crops, and a strategic fertilizer management plan is critical to match the requirements of specific vegetable crops grown, so that either under- or over-fertilization does not occur. Moreover, the ability to recycle mineral nutrients is an essential part of fertility management systems to create optimal growing conditions for vegetable crops on rooftops [1,13], although yields are often lower with alternative nutrient sources compared to those most often used in ground level agricultural systems [14].

Although slow-release fertilizers are effective for use on extensive green roofs when slower-growing and lower-maintenance plants such as *Sedum* are grown, many vegetable plants require higher nutrient inputs and cannot usually be sustained throughout the entire growing season to produce high yields with only an initial application of a slow-release fertilizer material [13]. Although some vegetable

crops can produce adequate yields with low nutrient inputs, many have improved growth and yield with high nutrient inputs. For example, tomato growth and yields on an extensive green roof system improved as high amounts of plant available nutrients were made readily available for plant uptake, and high fruit yields were possible when fertility applications were made every week throughout the growing season [1]. However, the timing of nutrient application is also important, with lower amounts required when plants are smaller and increasing as plants develop to maturity. A green roof fertilization schedule should only provide enough fertilizer to maintain adequate plant growth without compromising yields, while at the same time, minimizing the amount of runoff contamination [6]. Thus, a major challenge is to provide proper amounts of nutrients to maximize growth without causing waste and potential runoff issues. Although green roofs offer a long list of environmental benefits, a serious concern is the contribution of nutrient runoff into storm water systems. Nutrient pollution is a widespread and serious environmental problem, with nitrogen and phosphorus pollutants causing much of that damage. Minimizing nutrient runoff is especially a challenge on vegetable crop extensive green roof systems due to shallow substrates having both low nutrient and water holding capacities. Furthermore, many vegetable crop plants require high nutrient inputs, which can directly lead to excessive nutrient applications resulting in elevated amounts of nutrient runoff unless properly managed. Suggested solutions include a calibrated fertigation program through trickle irrigation, or other alternatives such as capturing nutrient runoff and recycling back to the irrigation/fertigation systems.

3.9. Plant Materials (Vegetable Crop and Variety Selection)

Due to the shallow growing medium in extensive green roofs, vegetable crops were thought to be a poor fit for this type of production system. Herbaceous plants (such as vegetables) often require either deeper mediums or greater inputs (e.g., water or nutrients) than the more traditional extensive green roof plants (such as *Sedums*) [6,28,29]. Besides the additional input requirements, many vegetables, such as tomatoes and peppers, have roots that grow deep into the soil to provide plant support. In comparison, the shallow-rooted and drought tolerant *Sedum* spp. were thought to be the best choice for extensive green roofs due to their small size, low-growing habit, and low water use which related to minimal maintenance activities. Thus, most agree that crops most suitable for extensive green roof culture are those more shallow-rooted vegetables that also tend to be low growing in habit to reduce the effects of wind damage. Although many vegetables are available to grow in this system, lettuce, chicory (*Cichorium intybus*) and endive (*Cichorium endivia*) are crops that can effectively be produced on green roofs with adequate moisture inputs [30]. Salad green vegetable crops typically generate high yields in green roof culture, compared to many other vegetables, as production can be spread out over the growing season to provide consistent harvests, which makes these vegetables a viable option on rooftops [4]. Additionally, row covers may be used for these crops to further extend production beyond the typical growing season by moderating temperatures.

Vegetable and herb production in an extensive green roof is feasible and can be productive with proper management [14]. Since green roofs can be very hot during the summer months, it can be difficult to provide optimum growing conditions in this environment to sustain maximum growth and productivity of many vegetable and herb crops. This can directly relate to reduced plant survival rates in green roof mediums during dry or hot periods [21]. Since many vegetable plants can tolerate shallow medium depths [9], high temperatures tend to be more of a problem in a green roof environment than when vegetable plants are grown in soil at ground level, especially if there is no irrigation system to provide water for the resulting high evapotranspiration rates.

Another management concern is vegetable crop size at maturity. The most suitable vegetable varieties for extensive green roofs are those that are dwarf or determinate in growth habit, as they will minimize growth while providing significant yields. Moreover, most staking and/or trellising operations for plants are not really an option; and, any support system that is used must be secured to the roof in some way to avoid damaging the roof membrane and to remain intact during strong

winds. Since larger-sized vegetable plants must be secured to the roof in some manner to prevent wind damage, smaller-sized varieties would be less likely to suffer from wind damage. Wind exposure can destroy plantings of taller growing vegetable crops, like tomato and pepper, unless some type of windbreak is used to minimize damaging winds.

Light-weight mediums with limited organic matter also limits the success of seeding operations in an extensive green roof environment [12,21]. Smaller seed can often fall into deep gaps in the substrate material, resulting in no germination from either no moisture reaching the seed or being at an increased depth from which they cannot emerge. Therefore, vegetable transplant plugs can be used to enhance establishment and plant survival rates, although this requires either an added greenhouse production facility or additional costs to purchase vegetable plants. The added costs for vegetable transplants will often be a good investment considering inadequate stands that can result from directly seeding into extensive mediums on a green roof.

4. Vegetable Research on Southern Illinois University Carbondale (SIUC) Green Roof

The SIUC green roof is on top of a portion of the south wing of the Agriculture building and can hold up to 112 kg/m² of plants and media. The components of the SIUC green roof (from the bottom portion upwards) include a waterproof membrane layer (thermoplastic polyolefin), a soft fabric protection layer, a root barrier, an 'egg crate' style drainage layer, a filter fabric, ~8 cm of green roof mix (light-weight aggregate + organic matter), and plant material.

Several studies conducted on the SIUC green roof have indicated that numerous vegetable crops are suitable for production in this environment, although the greatest lessons learned were the importance of fertility management systems to provide sufficient amounts of mineral nutrients, and maintaining consistent moisture levels in the growing medium to create optimal growing conditions [1]. However, due to some of the issues discussed previously regarding green roof vegetable culture, especially vegetable crop suitability and fertility systems, a study was conducted on the SIUC green roof in the autumn growing season (September to December) during 2010 and 2011. This study evaluated the effectiveness of four different fertility treatments on the production of several shallow-rooted vegetables [kale, lettuce and radish (*Rhaphanus sativus*)] in a green roof environment using a randomized complete block design with 4 replications. The fertilizer treatments evaluated were: (1) Vermicompost tea (from composted coffee grounds); (2) Miracle Grow[®] fertilizer (Scotts Miracle-Gro Products Inc., Maryville, OH, USA); (3) Organic Miracle Grow[®] fertilizer (Scotts Miracle-Gro Products Inc.); and (4) no fertilizer. Although all treatments were in the same expanse of green roof media, no cross fertilizer contamination among plots occurred due to the center-to-center distance between each plot row (~0.6 m) and considering that all treatment applications were applied directly at the base of the plants. All crop plants evaluated were all relatively shallow-rooted and did not move into the adjacent plot medium. The green roof media had a 6.5 pH, organic matter content of 4.3%, and estimated Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca), and Magnesium (Mg) release of 101, 617, 250, 2798, and 491 kg/ha, respectively, with 70% Ca base saturation. Based on fertilizer analyses, all materials provided similar trace amounts of Ca, Mg, Sodium, Boron, Iron, Copper and Zinc. For specific major macronutrient content, Miracle Grow[®] had 1.6% N, 0.04% P, and 0.1% K; Organic Miracle Grow[®] had 0.7% N content and less than 0.01% P and K; and, Vermicompost tea provided 1.2% N, with P and K in trace amounts. Fertilizers were applied once per week to plants and irrigated 2 to 3 times per week with drip irrigation, depending upon moisture needs of plants. Over the entire growing season, approximately 18, 8, and 14 kg N/ha were added for Miracle Grow[®], Organic Miracle Grow[®], and Vermicompost tea treatments, respectively. Most of the applied N for Organic Miracle Grow[®] and Vermicompost tea treatments were in the organic form and were not readily available for plant uptake.

Data collected at the termination of the experiment included mature leaf chlorophyll content (estimated % N), leaf and root dry biomass (g), lettuce and kale plant height (cm), radish taproot diameter (cm), and % N, P, K, Ca, and Mg in mature leaves of all three crops. Data were analyzed

by ANOVA (SAS, Cary, N.C., USA), with no interactions ($p > 0.05$) detected for any variables between treatments and years; therefore, data were combined over years. Mean comparisons between treatments were made using Fisher's Protected Least Significant Difference (LSD) Test at ($p \leq 0.05$).

4.1. SIUC Green Roof Vegetable Research Results

Results from this study indicated that all crops evaluated could be effectively produced in an extensive green roof system with adequate nutrient inputs (Tables 2–4). Although, the high nutrient fertilizer (Miracle Grow[®]) provided the greatest leaf (kale and lettuce) and root biomass (radish), the Organic Miracle Grow[®] treatments that provided lower amounts of nutrients would most likely be sufficient in most instances. The amount of chlorophyll also tended to be at the highest levels in the Miracle Grow[®] and Organic Miracle Grow[®] treatments for kale, lettuce and radish leaves. The overall amount of plant growth as detected by plant heights also tended to be highest in these two fertilizer treatments. For all crops evaluated, N leaf nutrient content also tended to be the greatest in the Miracle Grow[®] treatment, although this was not the case for P, K, Ca and Mg levels. The vermicompost tea applications provided consistent low levels of N across all crops evaluated. Besides N content in kale leaves, most other macronutrients tended to be lower when Miracle Grow[®] was used compared to the other fertility treatments, which had similar higher values. In comparison, the Organic Miracle Grow[®] treatment had N leaf content similar to Miracle Grow[®], but greater levels of K, Ca and Mg. In lettuce leaves, P content was higher when Miracle Grow[®] was used compared to all other treatments, although K, Ca, and Mg levels were relatively low with this fertilizer source. Again, Organic Miracle Grow[®] provided similar lettuce leaf N levels compared to Miracle Grow[®]. This indicates that Organic Miracle Grow[®] may be a better fit for salad green crops (such as kale and lettuce), when grown in a green roof environment, since it provided consistently higher macro-nutrient contents in leaves while delivering less overall leachable NO_3^- compared to Miracle Grow[®]. For radish leaf macronutrient content, Ca content was low when Miracle Grow[®] was used compared to other treatments, although P, K, and Mg were similar to the other treatments evaluated.

Table 2. Influence of fertilizer type on 'Red Russian' kale growth in an extensive green roof system at Southern Illinois University Carbondale combined over the 2010 and 2011 autumn growing seasons.

Fertilizer Treatment	Dry Biomass (g)			Plant ht (cm)	Leaf Nutrient Content (%)				
	SPAD	Leaf	Root		N	P	K	Ca	Mg
Control	41.8 a	2.1 b	0.3 a	8.2 b	5.0 bc	0.6 b	4.2 a	1.6 a	0.3 ab
Organic Miracle Grow	47.8 b	2.6 a	0.4 a	8.8 a	5.4 ab	0.6 b	4.0 a	1.5 a	0.3 ab
Miracle Grow	49.2 b	3.2 a	0.4 a	9.5 a	5.7 a	0.7 a	3.4 b	1.2 b	0.2 b
Tea Compost	41.7 a	2.1 b	0.3 a	8.1 b	4.8 c	0.6 b	4.4 a	1.7 a	0.4 a

Means within the same column followed by the same letter are not significantly different according to Fisher's protected LSD at $p \leq 0.05$.

Table 3. Influence of fertilizer type on 'Red Sails' lettuce growth in an extensive green roof system at Southern Illinois University Carbondale combined over the 2010 and 2011 autumn growing seasons.

Fertilizer Treatment	Dry Biomass (g)			Plant ht (cm)	Leaf Nutrient Content (%)				
	SPAD	Leaf	Root		N	P	K	Ca	Mg
Control	22.9 bc	1.1 b	0.1 b	5.2 b	4.8 a	0.7 b	5.9 a	1.0 a	0.4 a
Organic Miracle Grow	26.5 b	1.9 a	0.1 b	5.1 b	5.0 a	0.6 c	4.5 b	0.8 b	0.3 b
Miracle Grow	30.7 a	2.3 a	0.2 a	6.1 a	5.4 a	0.8 a	5.1 ab	0.6 c	0.3 b
Tea Compost	12.2 c	1.2 b	0.2 a	4.9 b	4.0 b	0.7 b	5.9 a	0.8 b	0.3 b

Means within the same column followed by the same letter are not significantly different according to Fisher's protected LSD at $p \leq 0.05$.

Table 4. Influence of fertilizer type on ‘Easter Egg’ radish growth in an extensive green roof system at Southern Illinois University Carbondale combined over the 2010 and 2011 autumn growing seasons.

Fertilizer Treatment	Dry Biomass (g)			Taproot	Leaf Nutrient Content (%)				
	SPAD	Leaf	Root	Diameter (cm)	N	P	K	Ca	Mg
Control	39.4 bc	0.5 a	0.5 a	2.0 b	5.0 bc	0.5 b	2.5 bc	2.7 a	0.5 a
Organic Miracle Grow	41.9 ab	0.5 a	0.6 a	1.9 b	5.2 b	0.5 b	2.3 c	2.5 a	0.4 b
Miracle Grow	44.4 a	0.5 a	0.6 a	4.2 a	5.7 a	0.6 b	3.0 a	1.8 b	0.4 b
Tea Compost	38.7 c	0.5 a	0.5 a	1.7 b	4.5 c	0.9 a	2.8 ab	2.7 a	0.5 a

Means within the same column followed by the same letter are not significantly different according to Fisher’s protected LSD at $p \leq 0.05$.

4.2. SIUC Green Roof Vegetable Research Conclusions

Nutrient management is a critical component of vegetable production in a green roof environment. Better fertility management systems need to be developed to create optimal growing conditions for vegetable crops on rooftops [1]. Our study indicated that although lettuce, kale and radish can be produced effectively in an extensive green roof medium, nutrient applications are required to maximize their productivity. The Miracle Grow[®] treatments provided the highest applied nutrient levels based on recommended rates, which related to the greatest plant growth response. However, over-fertilization with Miracle Grow[®] probably occurred, which most likely resulted in high amounts of nutrient leaching and runoff. The Organic Miracle Grow[®] fertilizer was a more sustainable nutrient fertilizer source for a green roof system due to less plant available nutrients applied based on recommended rates, and only resulted in a small decrease in overall productivity for the shallow-rooted vegetables evaluated. Vegetable yields will normally increase with greater fertilizer use, but high rates applied will lead to nutrient leaching and runoff which can become a serious issue [21]. Moreover, use of products, such Organic Miracle Grow[®], that have sufficient nutrient availability (with little nutrient waste) or use of slow-release fertilizer type materials may be better suited for use in green roof environments compared to applications of high analysis fertilizers to prevent nutrient leaching and runoff.

Green roof mediums and fertility management systems are current challenges that limit productivity of vegetable crops in extensive systems [1]. Additionally, substrate nutrient and moisture holding capacity of a medium are concerns in green roof agricultural systems, especially when using extensive systems. Managing substrate fertility is often challenging because green roof substrates are engineered with less than 20% organic matter and combined with coarse, heat-expanded materials, such as slate or shale [13]; and, this tends to provide high material permeability and low cation-exchange capacity. Moreover, our research indicated that high nutrient applications are generally required to overcome these issues with most extensive green roof substrates to maximize vegetable crop yields (Tables 2–4). Although sufficient substrate fertility and moisture are essential to maximize green roof vegetable crop productivity, both are often difficult to manage effectively in extensive systems due to the mediums utilized.

5. Conclusions for Vegetable Production on Green Roofs

Food production and consumption in urban areas has become a global concern due to increasing numbers of people living in and moving to urbanized living spaces, which threatens food security [20]. Currently, many cities across the world are encouraging the widespread implementation of urban agriculture through policy reform. These policy changes present an opportunity to include vegetable production activities on green roofs in urban centers that have potential to provide many benefits to surrounding urban populations [7]. Given the needed demand for local foods and available opportunities in urban areas, there is great demand for developing food production programs for extensive green roofs.

Vegetable production using green roof technology is becoming an increasingly important part of urban agriculture. Rooftops create spaces for the production of edible vegetable crops, which

create opportunities for integrating agriculture into urban communities. Over the last few years, the production of agricultural products within urban center boundaries has received a great amount of attention due to the potential to provide sustainable food security to areas that typically depend on distant production regions for food products. However, a major challenge to urban agriculture is the availability of land space to use for food production. Green roofs can help to reclaim agricultural spaces that were thought lost as a result of construction, while also aiding in the protection of our environment through more sustainable practices [6]. If local urbanized agriculture is going to be a part of the solution to improve food security in cities, green roofs will have to be used as a space to assist in increasing and sustaining food production activities.

The use of available green roof space also creates the potential opportunity for expanding urban agricultural food production activities. Green roofs can help in the creation of sustainable urban agricultural systems in the future to produce fresh, nutritious vegetables for local communities. Rooftop agriculture can improve various ecosystem services, enrich urban biodiversity and reduce food insecurity. Food production provided by green roofs can help support and sustain food for urban communities, as well as provide a unique opportunity to effectively grow food in spaces that are typically unused [6]. Green roof agriculture also has the potential to connect urban consumers with their food, provide educational tools to teach those in the community about food production, and provide food for local residents and restaurants. Besides these benefits, green roofs are already being utilized in many parts of the world to improve the economic situations and food security of urban farmers [7]. The opportunities are really endless in the ways that green roof vegetable production can benefit urban communities.

There are several examples of green roofs throughout the world that are used to effectively produce a local and sustainable food source. Several cities, including Montreal, Toronto and New York [31,32], are well-known for their large-scale vegetable production activities on green roofs that provide local sourcing of food. Rooftop farms all over the world are now growing a wide range of vegetables each year on numerous types of buildings for local market sales. Local sustainable food movements are underway in many other cities with a focus of growing vegetables on green roofs, including Beijing, Chicago, Seattle, St. Petersburg, Paris, Vancouver, and Vienna to name a few. In Bologna, Italy, rooftop vegetable gardens could supply about 77% of the inhabitants' requirements for fresh produce [33]. However, even with this ongoing flourishing activity of food production on green roofs, rooftops are still underutilized for vegetable production activities for several reasons that were discussed previously, and this trend will most likely continue for the near future. Before green roof technology can be effectively incorporated into urban agriculture on a larger scale, there are numerous issues that must be addressed including reducing installation costs, large-scale assessments of weight load limitations for numerous buildings, and improvement of numerous management practices to ensure that the benefits of green roofs, such as energy savings and storm water management, are still provided to urban communities [7]. Moreover, although vegetables and herbs are now being grown on some green roofs, there is currently little information on how to best optimize yield of these crops in a green roof environment. A wide variety of vegetable products have been produced on green roofs worldwide, although some vegetable crops are better suited to extensive green roof production activities than others; for example, crops such as lettuce, kale, and other salad greens have shown to be highly productivity in extensive systems with minimal soil depths [5,30]. Moreover, our results also provide more support that shallow-rooted crops including lettuce, kale and radish make excellent crops in an extensive green roof environment (Tables 2–4). Although, other deeper-rooted vegetable crops can also be grown in extensive systems [1,14], they will require more attention to their nutrient and moisture inputs to maximize productivity.

There is a growing interest in utilization of urban rooftops as areas for food production. Currently, urban agricultural activities on rooftops are minimal, but could become an important part of future food production in cities [11,31]. The real impact will be the scale at which green roof vegetable production systems will be implemented as a part of urban agriculture. The utilization of alternative

agricultural production systems, such as green roof technologies, will unquestionably become of increasing importance as human populations increase and become more urbanized. Despite numerous limitations to current implementations of green roofs for vegetable production, these systems will increasingly become more important as urban consumers become more interested in local foods for their families. The cultivation of food on buildings is a key component to making cities multi-functional, and contributing to their sustainability and habitability [11,20]. However, green roofs are not the total solution to provide food security to cities, but they should be viewed as a supplement to other sources of food production, as well as the role that they can play in planning future urban agricultural systems. This worldwide movement will continue to flourish in the years to come, and most likely become an important part of future urban agricultural systems.

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