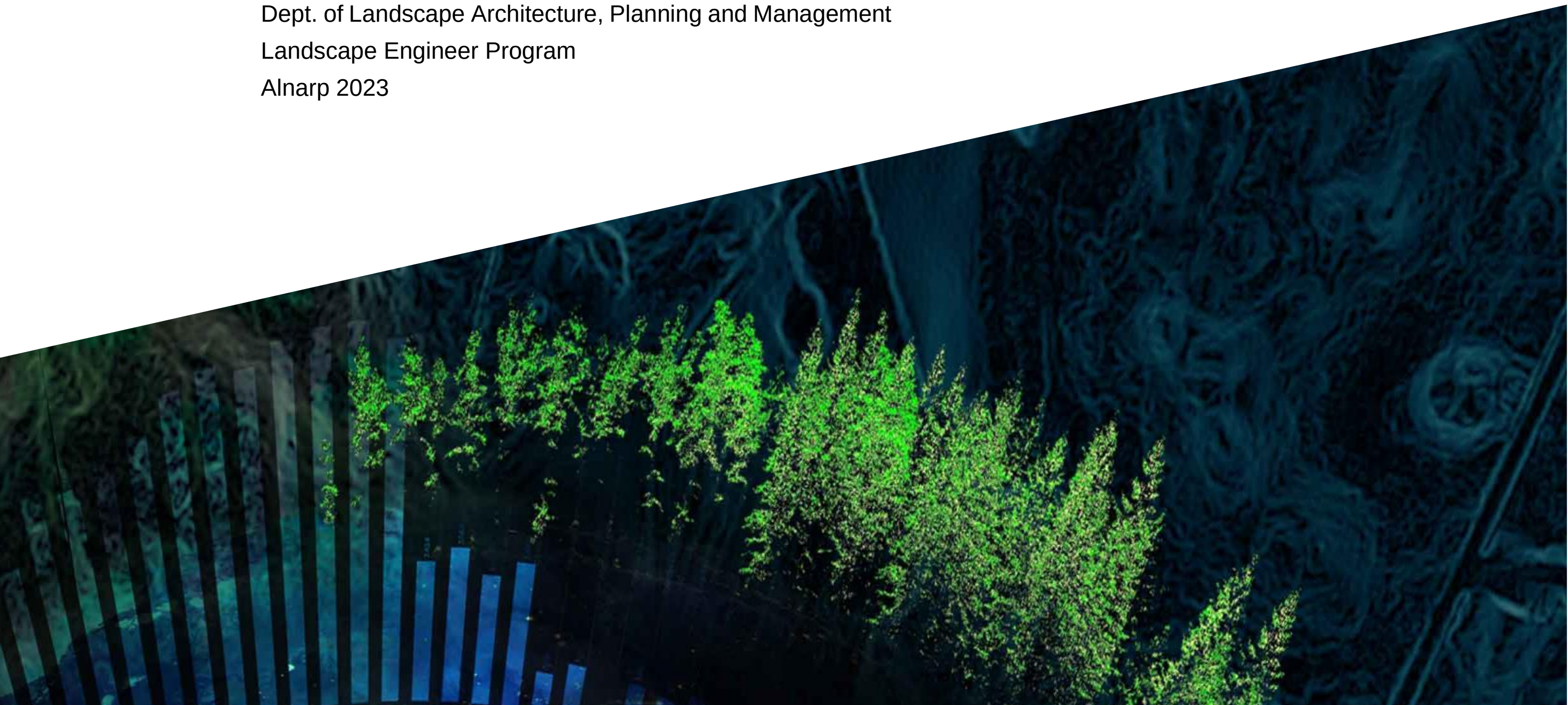
GROWING ON THE ROOF

BUT IN WHAT?

EXAMINING SUBSTRATES/GROWING MEDIA FOR ROOFTOP FARMING

Mikael Brocki

Degree project/Independent project • 15 credits
Swedish University of Agricultural Sciences, SLU
Dept. of Landscape Architecture, Planning and Management
Landscape Engineer Program
Alnarp 2023



GROWING ON THE ROOF – BUT IN WHAT? – EXAMINING SUBSTRATES/GROWING MEDIA FOR ROOFTOP FARMING

Mikael Brocki

Supervisor:	**Ishi Buffam, Swedish University of Agricultural Sciences, Department of Landscape Architecture, Planning and Management**
Assistant supervisor:	Karin Blombäck, Swedish University of Agricultural Sciences, Department of Soil and Environment
Examiner:	Tobias Emilsson, Swedish University of Agricultural Sciences, Department of Landscape Architecture, Planning and Management

Credits:	15
Level:	G2E
Course title:	Självständigt arbete i Landskapsarkitektur
Course code:	EX0841
Program/education:	Landscape Engineer Program
Course coordinating dept:	Department of Landscape Architecture, Planning and Management
Place of publication:	Alnarp
Year of publication:	2023
Keywords:	Urban rooftop agriculture, URTA, green roof, substrate, growing medium, organic matter, compost, vegetable, crop, yield, lettuce, tomato, pore, pore-size distribution

Swedish University of Agricultural Sciences
Faculty of Landscape Architecture, Horticulture and Crop Production Sciences
Department of Landscape Architecture, Planning and Management

Abstract

Urban Rooftop Agriculture (URTA) is a novel field within urban vegetable production, which can help create access to local food in a rapidly urbanizing world. For these systems to succeed, it is vital to implement a proper choice of substrate/growing medium (SGM). This study uses a literary synthesis, to analyze URTA SGM by investigating three of its key features, namely components, depth, and organic matter (OM) type and amount, with the intention of facilitating thoughts for future research and providing URTA-stakeholders with guidelines for choice of SGM. Results indicate that leafy vegetables and tomatoes can be cultivated in URTA-systems, potentially delivering yields comparable to conventional in-ground farming, using a wide range of SGM-substances, depths, and OM sources. It is not advisable to advocate for one specific SGM-substance. Instead URTA-farmers should strive to integrate locally produced light-weight material with numerous internal pores into their SGM. Shallow depths, corresponding to those found in extensive green roof systems (<15 cm) suffice for satisfactory URTA-yields. Continuous OM-/compost addition is a necessity for URTA-systems and consequently the proportion of OM/compost exceeds guidelines for more conventional green roof systems. More research is needed to understand the behavior of specific compost components in relation to density and URTA-crop production. An advanced knowledge of soil science is vital for engineering an URTA SGM that is light-weight simultaneously providing for sufficient cation exchange capacity (CEC), aeration, plant available water (PAW) and permeability. Therefore professionals, such as landscape engineers play a central role in URTA-SGM implementation.

Keywords: Urban rooftop agriculture, URTA, rooftop farming, green roof, vegetable, substrate, growing medium, organic matter, compost, vegetable, crop, yield, lettuce, tomato, pore, pore-size distribution

TABLE OF CONTENTS

TABLE OF TABLES

Abbreviations

CEC	Cation Exchange Capacity
FLL	Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau[1]
OM	Organic Matter
PAW	Plant Available Water
SGM	Substrate and Growing Medium
URTA	Urban Rooftop Agriculture
WHC	Water Holding Capacity

---

[1] The German Landscape Research, Development and Construction Society.

1. INTRODUCTION

1.1 Background and Rationale for Study

The concept of implementing green roofs as an element in city planning has existed for centuries. Roof gardens functioning as compensating factors for lost space on the ground in Mediterranean Cities, is an example of this (Lehman 2014).

In turn, decreased ground space is connected to urbanization and densification, which is a matter of concern for the development of sustainable cities. The current world population of 7.6 billion is expected to increase to 9.8 billion by 2050 (United Nations 2017). By this time, the urban population is expected to escalate from 55 to 68% of the total world population (United Nations 2018). The shift from rural to urban living not only alters land use, but also influences the local microclimate through displacement of nature (Lehman 2014). Biotic and abiotic characteristics of ecosystems are disrupted (Grimm et al. 2008), consequently changing the conditions for farming and food production (Seto & Ramankutty 2016; Satterthwaite et al. 2010; Andrade et al. 2022).

The above-mentioned challenges connected to urbanization with adjacent climate change leading to altered precipitation patterns and more frequent extreme weather events, is predicted to generate a significant increase in demand for agricultural yields, globally. This is aggravated by the fact that 40% of arable land is considered to be degraded (Fischer et al. 2011).

The current rate of urbanization rate leads to an abundance of available roof top space within localized areas. In New York City for example, there are approximately 154 000 000 m^2 acres of rooftops (Ackerman et al. 2012)[2]. These vacant areas have potential for becoming spaces, providing ecosystem services for urban inhabitants (Gasperi et al. 2016). It seems probable that the utilization of green roofs will increase in future city planning. There is much research emphasizing the benefits of green roofs in urban settings, such as, providing

---

[2] The authors refer to approximately 38 000 acres (Ackerman et al. 2012).

microhabitats improving pollinator diversity (Walters & Midden 2018); contributing to real estate energy savings (Gao et al. 2017; Begum et al. 2021); facilitating air purification (Begum et al. 2021); mitigating the urban heat island phenomenon (Ibid); assisting in stormwater management (Stovin 2010) and being a component of "sponge cities" (Gong et al. 2019).

Positive effects such as encouraging social justice and equality (Cohen & Reynolds 2014); offering platforms for education (Ibid.) and creating job opportunities (Begum et al. 2022), has been ascribed to urban rooftop agriculture (URTA). But several authors have noticed that there is a knowledge gap when it comes to rooftop farming (Whittinghill 2022[3]; Whittinghill & Rowe 2012, Shafique et al. 2018).

Nonetheless, there is an emerging scientific interest in the phenomenon of URTA (Harada et al. 2018b) and researchers predict that the flat areas of urban roof tops will become a progressively greater component in urban vegetable production (Calheiros & Stefanakis 2021). In other words, urban roof tops can become spaces for urban horticulture (Gasperi et al. 2016). Concerning crop production, URTA can deliver yields comparable to conventional in-ground farming (Whittinghill et al. 2016b), thereby having potential for "local food production"[4] (Sisco et al. 2017:133). For example, Orsini et al. (2018), suggest that about 332 000 m^2 of roof tops in the city of Bologna, Italy, could provide for 77% of the city's vegetable requirements[5] and Nasr et al. (2010), state that 25% of eligible roof top space in Toronto, Canada, can produce 10% of local fresh vegetable demands.

Pressure to cultivate on rooftops is likely to increase, as the current rate of urbanization continues and the demand for locally produced food steadily rises (Walters & Midden 2018). URTA can provide an opportunity for local agricultural production (Ibid; Rodriguez-Delfin et al. 2017, Ackerman et al. 2012; Benis et al. 2018). Currently, a large variety of crops ranging from root vegetables to herbaceous plants are cultivated in URTA-systems (Whittinghill et al. 2013).

As compelling as these suggestions might be, clear guidelines are lacking in terms of best management practice regarding factors such as, substrate and growing medium (SGM)-components, weight limitations and water-quality issues in relation to URTA (Whittinghill & Rowe 2012). Hence, it appears that further research is needed to achieve a level of standardization for URTA, providing stake holders with effective guidelines (Ouellette et al. 2013; Harada et al. 2017; Harada & Whitlow 2020; Ackerman et al. 2012).

---

[3] Leigh Whittinghill, Department of Environmental Science and Forestry Connecticut Agricultural Experiment Station, email. 2022-12-02.

[4] Referring to Beirut, LEBN. This statement is explained further in chapter 2.1.

[5] The authors refer to approximately 82 acres.

Many SGM-mixes are currently being used but scientific consensus on this topic has not yet been achieved (Whittinghill 2022[6]). Consequently, there is still a lot of work to be done investigating characteristics of included components (Walters & Midden 2018).

1.2 Aims

URTA is a novel field that is gaining ground in the development of urban planning. It is currently in its infancy (Harada et al. 2018b) and there is a need for creating best management practices for this "novel ecosystem"[7] (Harada & Whitlow 2020:2; Kong et al. 2015).

Dorr et al. (2017) and Ouellette et al. (2013), state that management practices in relation to URTA have seldom been studied from a sustainability point of view. Together with Walters & Midden (2018); Eksi et al. (2015), Harada et al. (2018a), and Ouellette et al. (2013), they point out that choice of SGM is a key parameter for rooftop farms, that requires further scientific analysis. Proksch (2012:5), reinforces this by stating that: "The most critical component for the success of a green roof or rooftop farm is its substrate, which is characterized by its composition, depth and weight".

But there is no scientific consensus nor existing guidelines for composition of URTA SGM:s (Whittinghill 2022[8]). Instead, rooftop farmers tend to design their own recipes, customized for local conditions and needs (Ellis 2022[9]).

In light of this background, the primary aim of this study is to describe URTA SGM, by analyzing its key features: components, depth, and organic matter (OM)[10]. Secondary, it is intended that this information will facilitate thoughts for future research, thereby generating ideas for further development of choice concerning SGM for rooftop farms. Lastly, as a consequence of presented evidence, coupled with a discussion, guidelines for proper choice of URTA SGM will be suggested for rooftop farmers.

---

[6] Leigh Whittinghill, Department of Environmental Science and Forestry Connecticut Agricultural Experiment Station, email 2023-01-11.

[7] This phenomenon can be described as an urban ecosystem with no equivalent in the natural environment (Harada & Whitlow 2020:2).

[8] Leigh Whittinghill, Department of Environmental Science and Forestry Connecticut Agricultural Experiment Station, email 2022-12-02.

[9] Pete Ellis, Senior Project Manager, Recover Green Roofs, email 2022-11-23.

[10] Harada et al. (2017:279), confirm the significance of these variables for URTA, referring to roof bearing capacity and nutrient and water retention, by stating that: "Among the most important soil properties affecting these are depth, composition, and pore-size distribution".

1.3 Research Questions

In order to achieve the aims, the following questions function as a framework for description and analysis.

1. How can URTA SGM be understood by examining components, depth and OM content and type as key features?

2. Which guidelines regarding URTA SGM, can be given to rooftop farmers?

1.4 Scope and Delimitations

Within the field of landscape engineering the discourse of green, blue and grey infrastructure is customarily discussed in terms of “ecosystem services”[11]. In this regard, many positive attributes have been attributed to green roofs. The scope of this study is limited to the analysis of SGM associated with URTA. However, as many factors for green roofs and URTA overlap, parallels between these related topics will be used.

Naturally, crop production is a central goal of agricultural endeavors. Leafy vegetables and tomato (*Solanum lysopersicum cvs*.) are used as exemplars when analyzing the effectiveness of different SGM:s, because of their differing demands for rooting depths. Lettuce is considered as shallow-rooted with an effective root zone of approximately 15 cm. Conversely, tomato is classified as deep-rooted, with an effective root zone of approximately 60 cm (Lott & Hammond 2013).

As with conventional on-ground agriculture, the success of URTA is dependent on ample supplies of nutrients (Whittinghill et al. 2016b). Satisfactory, crop production requires sufficient amounts of nitrogen, phosporus and potassium, whereas tomato demands higher levels of potassium than lettuce (Reiners et al. 2019). But an in-depth analysis of this is not to be found within this work. Instead, this aspect will be discussed briefly in relation to OM-additions, which commonly serve as a source of nutrients in URTA-systems[12].

Neither weather conditions nor phenology will be accounted for. This may be considered as a conceptual weakness, since geographical location affecting weather

---

[11] Ecosystem services are defined as benefits for people and society offered by urban nature. For a thorough description of this phenomenon, see Barton et al. 2020.

[12] See chapter 2.3.

conditions, is an important factor influencing productivity (Kazemi & Mohorko 2017). Consequently, it will also likely affect the relationship between SGM-characteristics and plant performance.

This study is solely dedicated to research concerning solid SGM:s, which is by far the most common method for building related growing systems (Thomaier et al. 2014) and the main focus is placed on SGM:s installed directly on the rooftop.
SGM:s can be placed 1) directly onto the roof, or 2) or in vessels such as trays and/or containers and there is no consensus regarding approach (Thomaier et al. 2014). The first approach more closely resembles conventional on-ground farming and is the primary focus of this study. However, many URTA SGM-experiments have been conducted in containers, where these vessels are constructed similar to conventional green roof systems[13]. Such studies have been included in this study, as have results from greenhouses on rooftops, which are becoming increasingly popular (Buehle & Junge 2014; Benis et al. 2018).

1.5 Material and Methodology

This thesis is a literature synthesis, where scientific articles constitute the bulk of sources. Additional information from relevant books has been analyzed and incorporated into the study.

Search terms such as: “green roof substrate”; “green roof growing media”; “rooftop agriculture”; “rooftop farm substrate”; “rooftop farm growing media”, were applied to the search engines: Primo (SLU[14] library resource) and Google Scholar. As an extension of this, relevant sources used by prominent researchers within the field were followed for further analysis.

Furthermore, interviews through email and zoom with researchers, rooftop farmers and companies providing SGM:s for URTA, have been conducted. These contacts were utilized more as an exploration of the discipline rather than as primary data sources. Some details from these sources are found in this work, but they should be viewed as supplementary to the main literature analysis.

---

[13] See for example Nektarios et al. 2022; Eksi & Rowe 2016.

[14] The Swedish University of Agricultural Sciences

1.6 Green Roof Systems

A green roof is a roof with vegetation over a structure, intended to offer several ecosystem services. A formal distinction is made between extensive and intensive green roofs. Popularly, SGM-depth is used as a division between the two categories, with shallower depths connected to the former and deeper depths linked to the latter (Ampin et al. 2010)[15]. But according to The Swedish guidelines for green roofs, level of maintenance should be used when separating these two systems (Pettersson Skog et al. 2021), where intensive green roofs are distinguished by a more intensive maintenance regimen than its counterpart. The German (FLL[16] 2018), also link extensive green roofs to lower maintenance levels and intensive green roof systems to higher ones. Furthermore, the FFL and British guidelines (GRO 2014), refer to systems by depth, similar to that found in Oberndorfer et al. (2008) and Berardi et al. (2014)[17].

Extensive green roofs are not constructed for pedestrian traffic, but to be viewed from a distance. They contain resilient plants, with a high tolerance for stressors such as drought. Hence, they can develop in shallow SGM-depths and irrigation is only conducted initially upon construction (GRO 2014; FLL 2018). In contrast, intensive green roofs more closely resemble on-ground habitats, allowing a potentially unlimited selection of plants[18]. However, more complex plant communities generate higher maintenance demands for sufficient plant water and nutrient needs. Requiring a sturdier construction set-up, these systems can also be used for recreational purposes (Ibid.).

There is also a middle ground between extensive and intensive green roofs, namely that of simple intensive (FFL 2018)/semi-intensive systems (GRO 2014). These green roofs are characterized by an intermediate depth[19], which can still support rich vegetation, including shrubs and bushy plants. Consequently, maintenance demands are dependent on plant selection (GRO 2014).

Furthermore, a distinction is made between single-layered green roof systems where drainage and SGM are integrated into one unit, and multi-layered units. “Blue green roofs” are examples of the latter. Having separate layers for water management[20] and SGM, they enhance stormwater management, through a more complex approach. Plastic cassettes and/or drainage mats are incorporated as parts

---

[15] See for example, Oberndorfer et al. (2008) and Berardi et al. (2014), who attribute SGM-depths below 20 cm to extensive green roofs and 20 cm and above to intensive green roofs.

[16] Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL), functions as a standard for general green roof- and URTA-research (Lehmann 2014).

[17] See footnote 15.

[18] Green roofs with greater SGM-depths (i.e., intensive) can accommodate trees (Savi et al. 2014; Pettersson Skog et al. 2021), although this is rare.

[19] 10-20 cm.

[20] I.e., drainage, irrigation and or water uptake.

of a water reservoir, whose levels can be regulated actively[21], thus controlling water retention and release. Plant metabolism passively contributes to the same mechanisms, but the effect of evapotranspiration is negligent compared to the mechanically adjusted system. Considering plant water and nutrient supply, blue green roofs should, according to Pettersson Skog et al. (2021), allow for capillary rise from water storage components to the vegetation layer. Considering that a green roof is a system operating without groundwater contact, this can constitute a challenge. However, plant available water (PAW) can be supported through the selection of particles and their corresponding size distribution (Ibid.).

1.7 Green Roof SGM

Appropriate choice of SMG is a crucial factor for successful green roof establishment and development (Kader et al. 2022). Recommendations for green roof SGM vary widely (Ampin et al. 2010) However, there are clear differences between a “natural” soil[22] and green roof SGM. A natural soil is developed in-situ over time, whereas a green roof SGM is a manufactured product, remotely produced. Moreover, natural soils generally offer a more pronounced structural stability over time. Green roof SGM:s, on the other hand, are usually more exposed to substrate loss due to a looser structure and external factors such as precipitation, sun and wind (Whittinghill & Rowe 2012; Ackerman et al. 2012), as well as internal factors such as biodegradation (Carrillo et al. 2012). Additionally, having no ground contact, green roof SGM:s are not able to accumulate in-ground biomass in comparison to conventional vegetation systems (Goldstein et al. 2016).

Considering component characteristics, a natural soil should not be used on green roofs. Especially silt and clay should be avoided since they reduce permeability and aeration and can retain too much water (Pettersson Skog et al. 2021). Consequently, their saturated bulk density could be too high, challenging roof load- bearing capacity[23]. Therefore, a green roof SGM needs to be adapted specific to purpose (Graceson et al. 2013b). Besides corresponding to weight-load limitations

---

[21] Through mechanics controlled digitally.

[22] “Natural soil” is here defined as a component consisting of sand, silt and/or clay, created by natural processes taking place in the crust of the earth.

[23] The inappropriateness of silt and clay as substrates for green roof SGM needs to be contextualized, linking factors to particle- and pore characteristics. A clarification of this is found in chapter 3.

and ensuring proper run-off, it should be able to form a stable structure as well as supplying plants with sufficient levels of nutrients, water, and air (Baryła et al. 2018; FFL 2018; GRO 2014; Pettersson Skog et al. 2018). Elstein et al (2008:80), express this in a clear manner: "…it should be light-weight, easy to install, have good insulating properties, good aeration, and a high moisture holding capacity. It would not leach large amounts of soluble solids but would have adequate cation exchange capacity (CEC) and fertility for plant growth". At "full water holding capacity"[24] (FLL 2018:82), it is recommended that a green roof SGM should entail no less than 10% air filled porosity (FFL 2018), which is necessary for adequate gas exchange at field capacity (Blombäck et al. 2021).

By rectifying particle-size distribution, green roof SGM:s can simultaneously be both light-weight and porous, thus allowing for adequate PAW and aeration. Normally, pore-size distributions curves are most appropriate for description of soil characteristics. Pettersson Skoog et al. (2021), confirm this but emphasize that such investigations are difficult and time demanding to conduct. Contrarily, particle-size distribution curves are more convenient and can still display a fairly representable view of SGM water holding capacity (WHC) and permeability. However, light-weight components with rich internal pore systems may generate misleading contextual information since a particle-size distribution curve is based on weight. Concretely, components such as pumice and biochar leave less of a mark on particle-size distribution curves, than do equally sized but heavier particles. This can potentially result in an underestimation of SGM WHC and permeability[25] (Ibid.).

Green roof SGM:s are completely or partially mineral based, where 80-100% of its volume consist of mineral particles and a maximum amount of 20% OM should be added to its composition (FLL 2018; Ampin et al. 2010)[26]. The FLL (2018), refer to components as: improved top and subsoils, mineral aggregates (with or without OM-additions) and substrate panels such as processed foam and fibers. Additionally, "foreign substances", such as tiles, glass, ceramics[27] and plastic material[28] can be incorporated (Ibid:84).

---

[24] The term "maximum water capacity" is defined by the FLL (2018:58) as: "the amount of water held by a water-saturated substance after dripping for two hours". In Germany this is achieved at 1.8 pF (total pressure), whereas the international standard method exposes substrates to 2,5 pF (Bundesanstalt für Gewässerkunde 2015).

[25] External micropores cannot be described in a particle-size distribution curve as their volume share is not representable in relation to its weight (Pettersson Skog et al. 2021).

[26] See chapter 2.3 for a more detailed description of OM.

[27] Should not exceed 0.3% of mass (FLL 2018).

[28] Should not exceed 0.1% of mass (Ibid.).

The Swedish green roof guidelines promote pumice as an ingredient for SGM:s, since it is lightweight and efficiently contributes to drainage, aeration and WHC, by having a large number of internal pores (Pettersson Skog et al. 2021). Ampin et al. (2010), confers this by further emphasizing its light weight and porous structure.

The Swedish guidelines also recommend biochar, by noting that it offers high CEC, WHC, nitrogen buffering and favorable conditions for microorganisms, enhancing microbial and mycorrhiza establishment (Pettersson Skoog et al. 2021). Werdin et al. (2021), furtherly endorse biochar as a green roof SGM-addition, concluding that it decreases bulk density[29] and increases WHC and PAW[30]. However, the same authors (Ibid.), noted that finer particles of biochar decreased infiltration rate and air-filled porosity, whereas the opposite was true for coarser particles. Additionally, Cao et al. (2014), reinforce the positive effects of biochar implementation. Biochar additions can also, to some degree, decrease nutrient leakage (Kuoppamäki et al. 2021).

Furthermore, SGM-additives in the form of peat, humus, wood, chips, sand, lava, and expanded clay, have been shown to offer sufficient WHC, permeability and density for green roof growth (Velazquez 2010 in Ouellette et al. 2013). Light-weight components such as different forms of pellets, brick, paper, and clay have also been suggested to positively influence plant growth and diversity on green roofs (Molineux et al. 2015). Likewise, Graceson et al. (2011) and Graceson et al. (2013b), incorporated brick in their trials, showing that crushed brick offers greater aeration and higher WHC, than crushed tile. The authors suggest that a comparably higher proportion of intra-particle space found in bricks can explain this phenomenon (Graceson et al. 2013a)[31]. Other artificial components such as foam (petrochemical based) and fiberglass have been proven to have potential for green roof SGM, by displaying favorable WHC and aeration. Similarly, Krawczyk et al. (2017), state that waste material such as silica, can be a viable component of green roof SGM, presenting values in accordance with FLL-standards (2018), regarding particle-size distribution, bulk density, mass, soil reaction and salinity. Furthermore, their results suggest that silica has a positive effect on plant growth and biomass. Bisceglie et al. (2014), also studied waste material[32]. They found

---

[29] The decrease concerns both dry and saturated bulk density. Particle size did not affect saturated bulk density (Werdin et al. 2021).

[30] Greater additions and smaller particles of biochar generated higher WHC and PAW (Ibid.).

[31] It is worth noting that the “foreign substances” (FLL 2018:84) (i.e., brick and tiles) in these studies, greatly exceed recommendations set by FLL (2018).

[32] I.e., “foreign substances” (FLL 2018:84).

granular waste (autoclave aerated concrete) to display values for WHC, OM and dry bulk density[33] comparable to lapillus and pumice[34].

---

[33] The authors present a “compaction curve”, where the highest value for wet bulk density is found at approximately 75% of moisture content (Bisceglie 2014: 359).

[34] These values also matched Italian standards for green roof SGM (Ibid.)

2. RESULTS

2.1 SGM-Components for URTA

Plant growth and yield enhancement, probably the key factors of URTA (Eksi et al. 2015)[35] are directly dependent on the characteristics of chosen SGM (Ouellette et al. 2013; Caputo et al. 2017). As with SGM:s for green roofs in general[36], SGM:s for URTA should be able to provide structure, permeability, water, aeration, permeability, and CEC (Rodriquez-Delfin et al. 2017). In addition, because of the particular goals of growing productively and harvesting, URTA SGM:s should be able to provide higher amounts of water and nutrients (Whittinghill et al. 2016b). But the coarse structure of green roof SGM:s may lead to URTA-nutrient deficiency (Ouellette et al. 2013), which is a concern for rooftop vegetable production (Whittinghill and Starry 2016). How these SGM:s can be altered and optimized to serve URTA-systems, in terms of vegetable production and nutrient leakage requires further research (Whittinghill et al. 2016a).

There are many SGM-components being used among URTA-farmers and the terminology applied for these is not uniform[37].

---

[35] This can be debated as several social ecosystem services are linked to URTA (see for example Begum et al. 2021b; Thomaier et al. 2014). In fact, social benefits might be the most significant contributor to its raison d'etre (Anastasia Cole Plakias, co-founder & Chief Impact Officer, Brooklyn Grange Farm, email 2022-11-23).

[36] See chapter 1.7.

[37] See table 2.

Table 2. SGM:s utilized on URTA-farms

ROOFTOP FARM	SGM
Avling Rooftop Farm (Toronto, CA)	Engineered growing medium with crushed brick[38]
Brooklyn Grange (NYC, USA)	Compost-based growing medium engineered specifically for green roofs, sourced from Rooflitesoil®, Naturecycle® and others[39]
Carrot Green Roof (Toronto, CA)	Various organic soils mostly from pure life soil® with added compost[40]
Chicago Botanic Garden (Chicago, USA)	Shale, compost (certified organic OMRI listed composted cow manure, landscape, and food scrap), and rock minerals[41]
Eagle Street Rooftop Farm (NYC, USA)	Mixture of compost, rock particles and shale[42]
PAKT Antwerpen, BE	Optigrün Intensive Substrate Urban Soil®[43]
Roots on the Roof (Vancouver, CA)	Local topsoil, compost, mulch (wood and leaves)[44]
Scandinavian Green Roof Institute (Malmö, SWE)	"Lightweight mixture" of pumice, biochar and some compost[45]
Urban Farm, Toronto Metropolitan University (Toronto, CA)	Zincoblend-F®[46]
Østergro (Copenhagen, DK)	"Lightweight soil" mixed with tilestone[47]

Even though, there are light-weight SGM:s designed for URTA (Caputo et al. 2017), there is no standard for composition (Whittinghill 2022[48], Ellis 2022[49]). Instead, rooftop farmers tend to design their own recipes, adapted to local

---

[38] Max Meighen, Founder, Avling Rooftop Farm, email 2022-11-23.

[39] Anastaisa Cole Plakias, co-founder & Chief Impact Officer, Brooklyn Grange Farm, email 2022-11-23.

[40] Priya Jain, Garden Coordinator, Carrot Green Roof, email 2023-01-29.

[41] Kelly Larsen, Associate Vice President of Community Engagement for Windy City Harvest, Chicago Botanic Garden, email 2023-01-24.

[42] Eagle Street Rooftop Farm (2012).

[43] PAKT, email 2023-03-13.

[44] Carly Hilbert, President, Roots on the Roof, email 2022-12-11.

[45] Hugo Settergren, Scandinavian Greenroof Institute, email 2022-11-30.

[46] Sharene Shafie, Research Coordinator, Urban Farm Toronto Metropolitan University, email 2022-11-24.

[47] Kristian Skaarup, Østergro Rooftop Farm, email 2022-11-22.

[48] Leigh Whittinghill, Department of Environmental Science and Forestry Connecticut Agricultural Experiment Station, email 2023-01-11.

[49] Pete Ellis, Senior Project Manager, Recover Green Roofs, email 2022-11-23.

conditions and needs (Ibid.)[50]. There is no clear consensus supporting any specific URTA SGM-components over another and many URTA:s operate on existing green roof technologies. Whittinghill et al. (2013:465), strengthen this assumption by stating that: “Rooftop vegetable gardening is a production system in urban agriculture, based on green roof technology”. Thomaier et al. (2014:44), reinforce this perception, by stating that rooftop farming projects often employ “less-sophisticated growing methods”. Considering this background, the most concise approach to the issue may be through review of green roof SGM-research in general (Perkins 2022)[51], amended by support of soil science.

The lack of specific guidelines for URTA is consistent across different countries. The German guidelines for green roofs make no implicit reference to URTA and only refers to “kitchen gardens” as a non-professional endeavor on intensive green roof systems (FLL 2018:23). The Swedish handbook for green roofs, vaguely touches upon the topic, by referring to URTA SGM:s as a mix of OM (such as compost and peat) and additional materials such as perlite or pumice (Pettersson Skog et al 2021). The British green roof code, shallowly describes the potential of URTA but offers no information about contextual SGM (GRO 2014).

Moreover, there do not seem to exist any comprehensive parameters describing crop growth and yield in URTA-research[52]. Together with the variety of URTA SGM:s, this discrepancy of methods complicates the analysis of URTA SGM-research.

In spite of this, there is research linking various SGM-components to URTA-vegetable production[53].

Table 3. URTA SGM-components in relation to crops and results[54]

SGM-components	**CROP**	**RESULT**	**STUDY**
Peatmoss & Perlite	Lettuce & chicory[55]	High shoot dry to shoot fresh weight-ratio	Cho et al. 2008
Foam & fiberglass	Kale[56]	Less effective than potting soil	Elstein et al. 2008

---

[50] For implemented SGM:s among URTA-practitioners, see table 2.

[51] Anastaisa Cole Plakias, co-founder & Chief Impact Officer, Brooklyn Grange Farm, email 2022-11-16.

[52] See table 1.

[53] See table 3. For a description about used parameters, see table 1.

[54] For a description of used parameters, see table 1.

[55] Cultivars not defined.

[56] *Brasica oleracea var. acephala* ‘Dwarf Green Curled Scotch’.

Crushed porcelain and compost	Lemon basil[57]	Similar to haydite, sand and compost	Eksi & Rowe 2016
Mulch, green waste, crushed wood & inoculated earthworms	Lettuce[58]	Yields similar to private vegetable gardens in Paris	Grard et al. 2018
Potting soil	Cherry tomato[59]	Yields similar to private vegetable gardens in Paris	Grard et al. 2018
Expanded clay pellets, spent mushroom substrate, green waste compost and mulch	Kale & cherry tomato[60]	Yields higher than professional standards for kale & yields – yields comparable to professional standards for cherry tomato	Grard et al. 2020
Pumice, heat treated clay, zeolite & compost	Lettuce & tomato[61]	“Reasonable yields”	Nektarios et al. 2022:12
“Common” soil & compost	Lettuce, black cabbage, chicory & tomato (plum & beefsteak)[62]	Low yields for lettuce, black, cabbage & chicory – high yields for tomato	Orsini et al. 2018
Expanded light-weight aggregates & compost	Tomato[63]	“Potential for tomato production”	Ouellette et al. 2013:12
Cardboard pellets, compost & mulch	Romain lettuce[64]	Adequate for local food production (Beirut, LEBN)	Sisco et al. 2017
Light-weight aggregates & OM	Black cabbage & lettuce[65]	“Can effectively be produced”	Walters & Midden 2018:13

---

[57] *Ocinum x citriodolum.*

[58] *Lactuca sativa.*

[59] *Lycopersicum esculentum var. cherry.*

[60] *Brassica oleracea* and *Lycopersicum esculentum var. cherry.*

[61] *Lactuca sativa* and *Solanum Lycopersicum.*

[62] *Lactusa sativa* ‘Canasta’, *Brasica oleracea var. palmifolia* ’Riccio Toscana’, *Chicorum intybus* ‘Trevisio’, *Lycopersicum esculentum var. cherry* ‘San Marzano’ and *Solanum Lycopersicum* ‘Caramba’.

[63] *Solanum Lycopersicum* ‘Bush Champion II’

[64] *Lactuca sativa var. longifolia*

[65] *Brassica napus* ‘Red Russian’ and *Lactuca sativa* ‘Red Sails’.

Haydite, heat-expanded shale, sand & leaf compost	Tomato, lemon basil & chives[66]	No difference in production in comparison to on-ground cultivation	Whittinghill et al. 2013
Renewed Earth® Kalamazoo, MI, USA	Tomato[67]	Yields comparable to on-ground farming[68]	Whittinghill et al. 2016b

As for conventional on-ground farming, vegetable production on rooftops requires high amounts of water and nutrients. In this context, it is interesting to note that Whittinghill et al. (2016b), needed an intensified nutrient regimen in order to produce tomato yields comparable to on-ground farming.

Mulching could be a method to counteract water loss through evaporation, thereby decreasing the intensification of water and nutrient maintenance. Some studies point towards the effectiveness of mulching for URTA-crop production (Grard et al. 2018; Grard et al. 2020; Sisco et al. 2017). But Whittinghill et al. (2016b), downplay the importance of mulching as it did not sufficiently reduce moisture loss, in their study. Consequently, it had no effect on lemon basil and chives biomass fresh weight. Neither was total yield of tomato affected by mulching. The experiments were done in September with a phenological temperature decrease, cloudy conditions, and increased frequency of precipitation events, which might have saturated the SGM. Furthermore, a continuous irrigation regimen increased SGM-moisture content. The authors ascribe these factors as potential explanations for the ineffectiveness of mulching.

Light-weight components being able to provide URTA-vegetables with their needs are recommended. Varela et al. (2021), studied biochar together with compost and soil and biochar mixed with soil[69]. They concluded that the soil and biochar-mix[70] was just as effective for lettuce (*Lactuca sativa*) growth and yield as the SGM including compost. Since biochar reduces SGM-dry bulk density and potentially nutrient leakage (Ibid.), they recommend it as an addition to URTA SGM:s. In search for effective and sustainable light-weight materials, Eksi & Rowe (2016) and Elstein et al. (2008) studied somewhat unorthodox components[71]. Crushed porcelain together with compost seems to benefit lemon basil growth (Eksi & Rowe

---

[66] *Solanum lycopersicum*, *Ocimum basilicum* and *Allium schoenoprasum*.

[67] *Solanum lycopersicum*.

[68] Reference measurements used were: Swiader and Ware 2002 (crop density) and USDA 2011 (harvest area yields).

[69] Soil used is described as, a typical commercial garden hortisol (Varela et al. 2021).

[70] It is noteworthy that the soil and biochar SGM was strongly acid (pH 5.0).

[71] See table 3.

2016) but exceeded the recommended limit for “foreign substances” (FLL 2018:84), which should constitute no more than 0.3% of the total SGM-volume.

2.2 SGM-Depths for URTA

The primary concern for URTA (as for green roofs in general) is the carrying capacity of the roof, which dictates the set-up of these systems (Whittinghill et al. 2013). Orsini et al. (2017), state that general construction guidelines for green roofs could be applicable to URTA-systems. However, Wang et al. (2021), point out that there is a proportional increase between green roof weights and SGM-depths, where an increase of SGM-depth from 10 to 15 cm generates a need for roof construction reinforcement, when integrating many existing green roof SGM-mixes (Cascone et al. 2018).

Of all the green roof components, SGM constitutes the greatest impact on weight-loads affecting the supporting roof (Pettersson Skog et al. 2021). The total weight-load upon the roof is defined by the casing, the plants and the SGM (Sisco et al. 2017), where dry bulk density and porosity are of particular importance at saturation state. Naturally, SGM and weight-load affect each other in a reciprocal manner, where the carrying capacity of the roof dictates the SGM-composition and vice versa. Thus, SGM-depth should be chosen from a multifaceted point of view, where several variables are considered (Rodriguez-Delfin et al. 2017; Whittinghill 2013). Pettersson Skog et al. (2021), explicitly mentions URTA in this context and emphasize weight-load factors such as wind, rain snowfall, gear and machinery, pedestrian traffic, and walking zones between rows of crop (Petterson et al. 2021). When calculating on weight-load, saturation is important as state can increase SGM-weight by 30% compared to dry conditions (Ibid). In this context, it is important to point out that porosity is the main factor determining WHC and thereby weight.

Generally, URTA-systems fall within the category of intensive green roofs, with SGM-depths deeper than 30 cm (Coffman & Martin 2004). But shallower depths of 7 to 30 cm are considered to suffice for varied and successful URTA-vegetable production (Pettersson Skog et al. 2021). Considering weight-load limits, the greatest potential of URTA, is probably accomplished in SGM-depths < 15 cm

(Walters & Stoelzle Midden 2018). In fact, there is research challenging the perception that greater depths are necessary for URTA[72].

Table 4. Depths connected to URTA-crop production[73]

DEPTH (cm)	CROP	STUDY
5 & 10	Lettuce and chicory	Cho et al. 2008
7.62	Tomato	Ouellette et al. 2013
10.5	Tomato, basil & chives	Whittinghill et al. 2013
12.7	Tomato	Whittinghill et al. 2016b
14	Lettuce	Varela et al. 2021
15	Romain Lettuce	Sisco et al. 2017
15	Kale and lettuce	Walters & Stoelze Midden 2018
30	Cherry tomato & lettuce	Grard et al. 2018
30	Cherry tomato & lettuce	Grard et al. 2020

2.3 Organic Matter for URTA SGM

The OM-components of the SGM, is a particularly important part of URTA-systems (Ouellette et al. 2013; Walters & Midden 2018; Whittinghill & Poudel 2020), where compost is the most common type of OM used (Matlock & Rowe 2017). But the appropriate proportion OM-additions to green roof SGM is a matter of debate (Ampin et al. 2010), and many types of OM and proportions are used in research[74].

---

[72] See table 4.

[73] For a view of results, see table 3.

[74] See table 5.

Table 5. Compost materials and compost proportions in research

STUDY	COMPOST MATERIAL	COMPOST-% OF TOTAL SGM
Dorr et al. (2017)	Compost waste from nearby city	N/A
Eksi et al. (2015)	Municipal yard waste compost	20%
Eksi & Rowe (2016)	Municipal compost	25%
Graceson et al. (2013)	Compost green waste	20%
Grard et al. (2020)	Green waste from public parks and private gardens; crushed wood from city garden parks	50%
Grard et al. (2020)	Green waste from urban public parks and green spaces	50%
Kong et al. (2015)	Commercial organic composted component and mushroom compost	25%
Nektarios et al. (2016)	Compost from grapevine marc	15%
Orsini et al. (2018) N/A	N/A	N/A
Ouellette et al. (2013)	Coffee-ground based vermicompost	5%
Sisco et al. (2017)	Recycled butchery offal	33%
Varela et al. (2017)	Community green waste	N/A
Walters & Midden 2018	N/A	N/A

For more traditional green roofs, the Swedish (Pettersson Skog et al. 2021) and British (GRO 2014) guidelines, refer to German standards (FLL 2018), where 4-6% of OM in relation to total SGM-volume is recommended for shallower systems (extensive) and 6-9% for deeper ones (intensive). A maximum OM-amendment is set to 20% (Ibid.). In contrast, Eksi et al. (2015) determined the optimal dosage of compost for URTA-vegetable yield to be 60-80% of SGM[75]. Admittedly, the FLL (2018), states that special vegetation[76] may require higher proportions of OM. Nonetheless, the recommended maximum amount of OM remains at 20% or below in order to minimize risk of fire (FLL 2018; GRO 2014), sagging, waterlogging and putrefaction (FLL 2018).

Some disadvantages have been found connected to the implementation of high proportions of OM in green roof systems. Ouellette et al. (2013), point to biodegeneration and SGM-shrinkage and Grard et al. (2018), noticed a considerable reduction of SGM during the timeframe of their study. This was also true for Harada et al. (2017), for whom the SGM diminished to roughly half of its initial depth after the first growing season. Although, earthworms have been linked to enhancement of crop yields (Grard et al. 2018), Dorr et al. (2017), found that inoculation of earthworms into the SGM, increased the speed of SGM-decomposition. In order to compensate for SGM-loss through compaction and biodegradation, Grard et al. (2018), added OM at the beginning of each cropping season. Graceson et al. (2013b), found that OM derived from composted green waste, as part of URTA SGM, was structurally stable for six months. When studying OM in relation to tiles and brick, they observed that small OM-particles, < 2 mm, adhered to larger mineral particles (Graceson et al. 2013a), thus forming somewhat of semi-artificial aggregates. This could possibly reduce SGM-loss.

Another potential disservice of a high proportion of compost OM-addition is increased nutrient leakage caused by OM-addition (Czemiel Berndtsson 2010; Buffam & Mitchell 2015). In fact, Whittinghill & Rowe (2012), point it out as a primary concern connected to URTA-systems. When analyzing URTA SGM:s, from an environmental sustainability point of view, Dorr et al. (2017), found that OM-additives in the form of compost resulted in increased nutrient leakage. This effect was most visible during the first year of SGM-establishment. By then, a heterogenous SGM-structure had not yet developed. Consequently, lacking adequate porosity and microbial biomass, nitrate retention for plant uptake was not possible. This implies that OM-enhanced URTA SGM:s, could potentially contribute to eutrophication of recipient waters[77]. Dorr et al. (2017), also concluded that URTA SGM:s infused with 50% compost, resulted in less contribution to eutrophication than the control-SGM, consisting of Sphagnum peat moss and composted bark. According to the authors, this can be explained by a complete stabilization of the SGM by the second year of SGM-establishment.

---

[75] The authors studied cucumbers (*Cucumis sativus*) and peppers (*Capsicum annuum*).

[76] In this context, I classify vegetables as special vegetation.

[77] Whitlow (2017), refers to this phenomenon as “dead zones” in the Chesapeake Bay and the Gulf of Mexico, being caused by agricultural nutrient leakage.

There is evidence that additions of compost enhance URTA SGM-properties, thereby improving yield capacity (Dorr et al. 2017). The higher the productivity of a green roof ecosystem, the higher the rate of nutrient uptake from the SGM, thus nutrient leaching can be minimized if the right balance between nutrient supply and demand is struck (Buffam and Mitchell 2015). The results of Kong et al. (2015), demonstrate that a municipal green waste compost system as part of SGM URTA, achieved the best balance between Swiss chard (*Beta Vulgaris*) yield enhancement and nitrogen-leakage.

Furthermore, Grard et al. (2018), claim that OM, as green waste in URTA-systems generates many ecosystem services. Ondono et al. (2014), concluded that the higher amount of compost, the more pronounced microbial activity. Dorr et al. (2017), also emphasize the environmentally sustainable effects of incorporating OM/compost to URTA-systems, as it is locally produced. This is of interest, as the proximity of green roof SGM production to the implementation site constitutes a growing demand among practitioners (Oberndorfer et. al. 2007).

When evaluating the effectiveness of OM-additions to URTA SGM:s, it is vital for these SGM:s to form a stable aggregate structure over time. Concerning conventional green roofs Emilsson & Rolf (2005), found that the OM of non-commercial substrates was rapidly decomposed. Peat being used as SGM on rooftops was lost within a year (Ibid.). The resulting shrinking of SGM due to biodegradation of OM, is one disadvantage of the high-rate OM-additions commonly used in URTA SGM:s (Ouellette et al. 2013). SGM:s with higher proportions of OM and/or finer particles, also tend to compact more easily, than SGM:s with a coarser structure, which contain more mineral particles. Petterson et al, (2017), emphasize that this can result in a build-up of layers. This could block vertical water transport, thereby decreasing PAW. Furthermore, finer particles can block spaces between bigger particles, thereby reducing aeration (Dunnett and Kingsbury 2008 in Graceson et al. 2011). However, the results of Grard et al. (2020) and Grard et al. (2015), seemingly contradict this, by suggesting that a distinct layering of SGM[78] benefits crop growth. These findings are strengthened by Wang et al. (2021), who suggest that a layered structured is beneficial for SGM-performance, as the upper layer offers permeability, and the lower layer efficiently retains water[79]. Logically, this would benefit crop development.

j

---

[78] The authors refer to this as “lasagne beds” (Grard et al 2015:24). In another study, the same technique is quoted as the “lasagna system” (Grard et al. 2020:8).

[79] The increased water retention came at a cost of increased roof load (Wang et al. 2021).

3. DISCUSSION

The primary aim of this study was to describe URTA SGM in relation to components, depth, and OM. This was intended to facilitate thoughts for future research, as well as to provide URTA-farmers with guidelines concerning the choice of SGM. To achieve these aims, a literature synthesis mainly based on scientific articles, was conducted. Furthermore, interviews with URTA-practitioners were used as a supplementary source of information.

3.1 Reflections on SGM-Components for URTA

As illustrated in this study, a wide range of SGM-components can generate effective growth and yield for leaf vegetables and tomatoes in URTA-settings. Additionally, there are positive results showing that several light-weight materials can be utilized for this. However, there are also some indications that heavier conventional components, such as potting soil are more efficient for tomato growth[80].

Intensive nutrient management is essential for URTA-crop production (Whittinghill et al. 2016b). Therefore, light-weight materials with numerous internal pores should be considered when choosing SGM. Contributing to SGM-heterogeneity with beneficial porosity, these components can increase PAW, aeration, CEC and nutrient availability. Within this context, crushed brick and biochar appear to be beneficial components.

When implementing SGM-components into URTA-systems, it is advisable to conduct thorough pre-investigations of particle-size distribution prior to installation (Petterson et al. 2021). This will give an estimate of pore-size distribution which impacts air/water conditions of the SGM. As already mentioned, for particles with a pronounced internal pore system, it can be difficult to assess pore-size distribution in relation to particle size. Abad et al. (2005), studied particle-size characteristics of coconut coir dust[81] and concluded that fractions of 0.125 – 1 mm in diameter had

---

[80] See for example Grard et al. 2018; Elstein et al. 2008.

[81] Considered to be a light-weight material for green roof systems.

the largest impact on air-water ratio. Although, being limited to coconut coir dust, these findings could still be relevant when engineering SGM:s suitable for URTA-crop production. Particle-size distribution dictates inter-particle porosity, hence air-water balance will depend on the ratio between them and the structure of the pore system they create. Larger pores provide SGM:s with enhanced aeration and drainage. But as they hold less water at increased gravitational pressure than do smaller pores, PAW can consequently be restricted. Furthermore, SGM-formation should contain colloids, which increase CEC, mostly due to their large total surface area, thereby improving cation binding capacity of the SGM.

There is a growing demand for locally derived SGM-components (Dorr et al. 2017; Oberndorfer et al. 2007). Exploring suitable URTA SGM:s for local conditions, could therefore be of special interest, when considering the contemporary Swedish rise of a new "Green Wave", a.k.a. "hipster" subculture, within which, locality and regionality is emphasized (Olsson 2015). Hence, imported matter such as pumice, coconut, lava, etc., might not fit current visions of renewable and sustainable SGM:s (Gruda 2012). This argues for crushed brick and biochar as viable substitutes for Swedish[82] URTA-systems, rather than e.g., pumice which is a popular green roof SGM-component. Considering the findings of Werdin et al. (2021)[83], particle-size distribution of biochar units, should first be analyzed in order to obtain favorable values for WHC and aeration. Local waste products could potentially be included in URTA SGM:s, as well. However, research on this topic is scarce and components would have to be scrutinized in terms of toxicity, to ensure food security.

For these reasons, it appears to be wise for URTA-farmers to adapt a sound skepticism towards integrating pre-manufactured general SGM-mixes, as it can counteract optimization for local conditions. Therefore, a global approach to URTA SGM-composition does not appear to be an effective method. Instead, components would preferably be chosen in accordance with local weather characteristics and needs for sustainability and crop production. In light of this, the current situation where SGM-composition varies among URTA-locations[84] is justified. Thus, criteria for choice, require thorough investigations prior to SGM-installation on rooftop farms, where principles of soil sciences are adapted. This view is reinforced by Harada et al. (2017:279), stating that: "Soil science is central to engineering soils that satisfy both the concerns of roof bearing capacity and nutrient and water

---

[82] As well as for other geographical locations where pumice cannot be found in the natural environment.

[83] See chapter 1.7.

[84] See chapter 2.1.

retention". This information speaks in favor of engaging soil scientists and/or landscape engineers at the initial stages of URTA-establishment.

3.2 Reflections on SGM-Depths for URTA

This study presents evidence that relatively shallow SGM-depths suffice for satisfactory yields for leafy vegetables and tomato[85], which can somewhat alleviate worries about exciding roof weight-load limits.

Although, a few included studies imply that greater depths would be beneficial for enhancement of related crop development, it cannot be ruled out that greater SGM-volumes could enhance URTA-vegetable production.

However, this would have to be analyzed in relation to SGM-features, primarily concerning particle and pore characteristics of included components. As suggested above, light-weight materials with a large proportion of internal pores can be crucial for SGM-behavior in relation to URTA-yields. Mineral particles need to be assessed from a trade-off perspective, explaining correlations between depths, particle- and pore-size distribution, dry bulk density, PAW and nutrient storage. Here, a schematic model helping URTA-farmers to evaluate potential gains and losses, would be beneficial.

Whittinghill & Rowe (2012), suggest that insufficient moisture can be rectified by increasing depth. However, this needs to be expanded on. Wang et al. (2021), found that it is not advisable to increase SGM-depths in order to enhance rainwater retention capacity, as its rate of increase declines beyond a certain point of depth. Furthermore, weight-load increases with SGM-depth increase linearly and most lightweight green roof SGM:s, exceed weight limits for retrofitted roofs when increased from 10 to 15 cm in depth (Cascone et al. 2018). Therefore, Wang et al. (2021), conclude that alteration of SGM-depth is more crucial for construction safety than SGM-components[86]. These recommendations are noteworthy as they align with the current study, providing evidence that both leafy vegetables and tomato can be grown in SGM-depths <15 cm, corresponding to general definitions of extensive green roof systems[87]. Shallower depths generate higher WCH per unit volume of SGM, as gravitational force will have less of an impact compared to deeper

---

[85] See table 3.

[86] Such a conclusion must be contextualized together with SGM-construction explaining particle- and pore-size distribution.

[87] For a definition of green roof systems, see chapter 1.6.

systems. However, by having a smaller water filled pore volume, shallower SGM:s will inevitably require a more intense water and nutrient maintenance regimen, compensating for its limited water storage.

3.3 Reflections on Organic Matter for URTA SGM

As presented by this work, OM-amendments in the form of compost to SGM is a crucial component for effective URTA-yields. However, it seems clear that these additions commonly exceed guidelines for traditional green roofs[88]. This is a matter of concern as OM facilitates aggregate stability, providing sufficient PAW[89], aeration and nutrients, thereby gaining vegetable growth. When considering concerns related to increased roof weight-loads due to OM, it should be noted that OM has a low dry bulk density. Worries about exceeded roof weight-load limits in connection to OM, could possibly be linked to its high WHC. However, as green roof SGM:s are designed for rapid drainage, OM saturated bulk density, ought not to be a pressing issue.

There is research arguing for the appropriateness of earthworm inoculation into URTA SGM. They can theoretically contribute to decreased roof weight-loads and enhanced URTA-vegetable production. By forming pathways[90] for water movement, they increase the hydraulic conductivity and thereby drainage. But even more importantly, they generate pores which are too big to hold capillary water. Thus, earthworm activity facilitates a heterogenous SGM-structure, balancing air-water ratio.

A wide variety of compost material are utilized in URTA-studies[91]. At the same time, there are scientific concerns that increased amounts of OM will lead to elevated roof weight-loads and nutrient leakage[92]. However, to my knowledge, evidence-based correlations between specific OM/compost components and the above-mentioned hazards, do not exist. Hence, research distinguishing effects concerning crop productivity, weight characteristics, nutrient leakage in relation to

---

[88] See for example FLL 2018.

[89] This is possible as aggregates contain inter- and intraparticle pores within a size range that can hold water at lower pressures than 150 m water column.

[90] I.e., pores.

[91] See table 5.

[92] Chapter 2.3 presents conflicting results on this topic.

specific OM/compost components, is desirable. This conclusion is reinforced by Matlock & Rowe (2017:240), stating that: “The impact of compost addition to an expanded aggregate substrate on any of these parameters cannot be predicted based solely on the amount of compost added. The degree and direction of changes are dependent on the particular properties of specific composts”. Thus, establishing a best management practice for appropriate OM/compost components for URTA, would not only serve crop production, but would also provide stakeholders with security and incentives for investment.

Furthermore, an acceptance of SGM-loss due to decomposition of OM, would most likely be necessary for URTA-famers. Consequently, continuous additions would be required for long term preservation of SGM-potency. In-situ compost systems could compensate for this disadvantage by mitigating the cumbersome and expensive logistics of adding on-ground OM up onto the roof. Furthermore, it would increase nutrient re-recirculation on rooftop farms, by re-using plant debris, which is a desired improvement for these systems (Walters & Midden 2018).

OM as mulch is an established agricultural method of decreasing surface evaporation, thereby facilitating crop growth (Lott & Hammond 2013). Mulch has been concluded not to be necessary for URTA-vegetable production (Whittinghill et al. 2016b) but further analysis exploring the effects of different kinds of mulch components, in relation to factors such as, nitrogen cycling and enhanced microbial activity during decomposition, would be relevant. How this would play out in URTA-settings is a matter for future research.

3.4 Reflections on Blue Green Roofs and URTA

Successful URTA-yields will require controlled and efficient nutrient and water management (Whittinghill et al. 2016a; Whittinghill et al. 2016b). Notably, URTA-systems operate without groundwater as a source for plant water uptake. On the contrary, the roof surface can be likened to an aquifuge, indicating that PAW can be challenged as a consequence of restricted capillary rise.

Considering these conditions, blue green roof systems could potentially be utilized to compensate for this shortcoming. Such an approach would resemble multi-layer systems, which is proposed by FLL (2018:74) for “intensive greening”. Incorporating a separate water retention layer can benefit WHC, evapotranspiration rates and plant health (Tan et al. 2017). Moreover, multi-layer systems with a segregated water storage and layered soil[93], can significantly mitigate plant water stress (Wang et al. 2021). Varying energy potentials and depths between layers[94], allow for vertical movement of water in both directions. This can potentially explain the favourable results for URTA-crop production when utilizing a multi- layered system[95].

For URTA-systems, the water reservoir as a bottom layer on blue green roof system, could theoretically function as an artificial groundwater source. The aquifuge would thereby be replaced by a permeable membrane, resulting in an increase of available water for plant uptake through capillary rise. This has been proposed as a relevant factor for vegetable production in rain gardens (Richards et al. 2015; Richards et al. 2017) and plant development on green roofs (Cirkel et al. 2018). Similarly, Voeten et al. (2016), found that a below SGM-water storage in a green roof system promotes a consistency in SGM-moisture content, even during fluctuating precipitation patterns. Li et al. (2019), suggest that this advantage is not achieved only by capillary rise from the water reservoir to the bottom layer[96], but also through evaporation from the water reservoir reaching the SGM.

Potentially, blue green roofs could increase re-circulation of water and nutrients on rooftop farms. This is of interest, as recycling water from precipitation and runoff could benefit URTA-production. Irrigation with mixed water[97] instead of potable water can increase URTA-yields with up to 22% (Begum et al. 2021). Blue green roofs as part of URTA-systems constitute a field for further research.

3.5 Additional Reflections on URTA SGM

There is a broad spectrum of parameters used to describe URTA-crop production[98]. This discrepancy complicates the effectiveness of evaluating specific SGM-components, depths, and organic matter for crop production in URTA-systems. Hence, a uniformity of contextual parameters, coupled with consensus regarding measurement techniques, would serve the progression of evidence based URTA SGM-knowledge.

---

[93] Comparable to that of the “lasagne principle” (Grard et al. 2015:23) or “lasagna system” (Grard et al. 2020:8) see footnote 101.

[94] Affecting the hydraulic gradient.

[95] See, chapter 2.3.

[96] I.e., a permeable structure.

[97] Consisting of grey water and rainwater.

[98] See table 1.

In sum, this work underlines the importance of SGM-porosity. Ultimately, pore-size distribution will determine the behavior of components, depth and OM and their effect on URTA-crop production. This implies that pore characteristics should be paramount in the decision making of URTA SGM.

4. CONCLUSIONS

Vegetables such as lettuce and tomato can be produced in URTA-settings, using a wide range of SGM-components, depths and OM-sources and amounts. Broad-sweeping and general recommendations advocating for one specific SGM-component over another, appear not to be desirable, as this could neglect local and contextual circumstances. Instead, URTA-farmers should seek to incorporate local light-weight components with numerous internal pores, into their SGM, which match local conditions and needs for sustainability and yield. These components need to simultaneously allow for ample WHC, aeration, permeability, and available nutrients, which can be conflicting characteristics difficult to combine. Therefore, URTA-farmers would benefit from engaging professionals with an advanced knowledge of soil science, such as landscape engineers, at an early stage of farm establishment.

Excessive roof weight-loads caused by URTA SGM is a main concern for URTA-stakeholders. Albeit, heavily dependent on pore characteristics[99], increases in SGM-depth generate greater strains on roof construction. Fortunately, URTA-farmers do not need to strive for increased SGM-depths, since depths corresponding to extensive green roof systems, suffice for satisfactory vegetable production. However, this leads to higher demands for water and nutrient management.

It is vital for URTA-farmers to add OM as compost to their SGM for satisfactory yields. However, proportions typically used for such additions exceed the established guidelines for green roofs. Therefore, more evidence is needed, correlating different compost materials with factors such as WHC, crop production and nutrient leakage.

Blue green roof systems could potentially benefit URTA-vegetable production and simultaneously provide for increased control, regarding nutrient leakage and weight-loads. Furthermore, it could facilitate URTA-sustainability, by contributing to re-circulation of water and nutrients on rooftop farms.

In order to achieve a broader knowledge of URTA SGM-efficiency for crop production, components, depth and OM would preferably be analyzed in relation to a greater number of crops. Such an approach goes beyond the scope of this study but would be a well-grounded and legitimate perspective for future investigations.

---

[99] I.e., Pore-size distribution and internal pore system of components.

References

Abad, M., Fornes, F., Carrion, C., Noguera, C., Noguera, C., Maquiera, A., Puchades, R. (2005).
Physical Properties of Various Coconut Coir Dusts Compared to Peat. *Horticultural Science*, 40, (7), 2138-2144.

Abdallah, A. M., Jat, H. S., Choudhary, M., Abdelaty, E. F., Sharma, P. C., and Jat, M. L. (2021).
Conservation Agriculture Effects on Soil Water Holding Capacity and Water-Saving Varied with Management Practices and Agroecological Conditions: A Review. *Agronomy*, 11, 1681.

Ackerman, K., Plunz, R., Conard, M., Katz, R., Dahlgren, E., Culligan, P. (2012).
The Potential for Urban Agriculture in New York City: Growing Capacity, Food Security, & Green Infrastructure. Columbia University: Urban Design Lab at the Earth Institute. http://urbandesignlab.columbia.edu/files/2015/04/4_urban_agriculture_nyc.pdf [2023-02-02].

Ampim, P. A. Y., Sloan, J. J., Cabrera, R. I., Harp, D. A., Jaber, F. H (2010).
Green Roof Growing Substrates: Types, Ingredients, Composition and Properties. *Journal of Environmental Horticulture*, 28 (4), 244–252.

Andrade, J. F., Cassman, K. G., Rattalino Edreira, J. I., Agus, F., Bala, A., Deng, N., Grassini, P. (2022).
Impact of urbanization trends on production of key staple crops. *Ambio*, 51, 1158–1167.

Barton, D. N., Gulsrud, N., Kabisch, N., Randrup, T. B. (2020).
Urban open space valuation for policymaking and management. In: Jansson, M. & Randrup, T. B. (eds.). *Urban open space governance and management*. New York: Routledge. 129-149.

Baryła, A., Karczmarczyk, A., Bus, A. (2018).
Role of Substrates Used for Green Roofs in Limiting Rainwater Runoff. *Journal of Ecological Engineering,* 19 (5), 86-92.

Begum, M. S., Bala, S. J., Saiful Islam, A. K. M. (2022).
Effect of Performance of Water Stashes Irrigation Approaches on Selected Species of Plant's Water Productivity in Urban Rooftop Agriculture with Respect to Climate Change. *Water,* 14, 7.

Begum, M. S., Bala, S. J., Saiful Islam, A. K. M., Roy, D. (2021).
Environmental and Social Dynamics of Urban Rooftop Agriculture (URTA) and Their Impacts on Microclimate Change. *Sustainability,* 13, 9053.

Benis, K., Turan, I., Reinhart, C., Ferrão, P. (2018).
Putting rooftops to use – A Cost-Benefit Analysis of food production vs. energy generation under Mediterranean climates. Cities, 78, 166–179.

Berardi, U., GhaffarianHoseini, A. H., GhaffarianHoseini, A. (2014).
State-of-the-art analysis of the environmental benefits of green roofs. *Applied Energy*, 115, 411–428.

Bisceglie, F., Gigante, E., Bergonzoni, M. (2014).
Utilization of waste Autoclaved Aerated Concrete as lighting material in the structure of a green roof. *Construction and Building Materials*, 69, 351-361.

Blombäck, K., Dahlin, S., Eriksson, J. (2021).
Markvetenskap för landskapsarkitekts och landskapsingenjörsutbildningarna i Uppsala. Uppsala: Department of Soil and Environment, Swedish University of Agricultural Sciences.

Buehler, D. & Junge, R. (2014).
Global Trends and Current Status of Commercial Urban Rooftop Farming. *Sustainability*, 8, 1108.

Buffam, I. & Mitchell, M. E. (2015).
Nutrient Cycling in Green Roof Ecosystems. In: Sutton, R. K. (ed.). *Green Roof Ecosystems*. Springer International Publishing Switzerland. 107-137.

Bundesanstalt für Gewässerkunde. (2015). *Geoportal: Soil-Water Parameters*.
https://geoportal.bafg.de/dokumente/had/42_43_44SoilWaterRetentionParameters.pdf [2023-05-03].

Campbell-Nelson, K. (2020).
2020-2021 New England Vegetable Management Guide. Amherst: University of Massachusetts – Centre for Agriculture, Food and the Environment, University of Massachusetts Extension Vegetable Program.

Cao, C, T. N., Farrell, C., Kristiansen, P, E., Rayner, J. P. (2014).
Biochar makes green roof substrates lighter and improves water supply to plants. *Ecological Engineering*, 71, 368–374.

Calheiros, C. S. C. & Stefanakis, A. I. (2021).
Green Roofs Towards Circular and Resilient Cities. *Circular Economy and Sustainability*, 1, 395–411.

Caputo, S., Iglesias, P., Rumble, H. (2017).
Elements of Rooftop Agriculture Design. In: Orsini, F., Dubbeling, M., de Zeeuw, H., Gianquinto, G (eds.). *Rooftop Urban Agriculture*. Springer International Publishing. 39-61.

Carrillo, L., Jauch, M., Meinken, E. (2012).
Determination of Substrate Quality for Extensive Green Roof According to FLL Guideline. *Acta Horticulturae*, 938, 431-436. https://www.actahort.org/books/938/938_56.htm [2023-02-02].

Cascone, S., Catania, F., Gagliano, A., Sciuto, G. (2018).
A comprehensive study on green roof performance for retrofitting existing buildings. *Building and Environment*, 136, 227–239.

Chen, H., Ma, J., Wei, J., Gong, X., Yu, X., Guo, H., Yanwen Zhao, Z. (2018).
Biochar increases plant growth and alters microbial communities via regulating the moisture and temperature of green roof substrates. *Science of the Total Environment*, 635, 333–342.

Cho, Y. Y. (2008).
Soil Depth Affects the Growth of Lettuce and Chickory in Extensive Green Roofs. *Horticulture Environment and Biotechnology*, 49 (6), 434-438.

Cirkel, D. G., Voortman, B. R., van Veen, T., Bartholomeus, R. P. (2018).
Evaporation from (Blue-)Green Roofs: Assessing the Benefits of a Storage and Capillary Irrigation System Based on Measurements and Modeling. *Water*, 10, 1253.

Coffman, R. R. & Martin, J. F. (2004).
The sustainability of an agricultural roof garden. In: Green Roofs for Healthy Cities (ed). *2nd Annual International Greening Rooftops for Sustainable Communities Conference, Awards, and Trade Show* June 2-4, Portland, USA. 485-503.

Cohen, N. & Reynolds, K. (2014).
Resource needs for a socially just and sustainable urban agriculture system: Lessons from New York City. *Renewable Agriculture and Food Systems*, 30 (1), 103–114.

Czemiel Berndtsson, J. (2010).
Green roof performance towards management of runoff water quantity and quality: A review. *Ecological Engineering*, 36, 351–360.

Dorr, E., Sanyé-Mengual, E., Gabrielle, B., Grard, B. J-P., Aubry, C. (2017).
Proper selection of substrates and crops enhances the sustainability of Paris rooftop garden. *Agronomy for Sustainable Development*, 37: 51.

Dunnet, N. & Kingsbury, N. (2004).
Planting Green Roofs and Living Walls. (2004). Portland: Timber Press.

Eagle Street Rooftop Farm. (2012).
Eagle Street Rooftop Farm, 2012 Farm Fact Sheet. http://rooftopfarms.org/wpcontent/uploads/2010/01/EagleStreetRooftopFarmFactSheet2010.pdf [2023-05-03].

Eksi, M. & Rowe, D. B. (2016).
Green roof substrates: Effect of recycled crushed porcelain and foamed glass on plant growth and water retention. *Urban Forestry & Urban Greening*, 20, 81–88.

Eksi, M., Rowe, D. B., Fernández-Canero, R., Cregg, B. M. (2015).
Effect of substrate compost percentage on green roof vegetable production. *Urban Forestry & Urban Greening*, 14, 315–322.

Elstein, J., Welbaum, G. E., Stewart, D. A., Borys, D. R. (2008).
Evaluating Growing Media for a Shallow-Rooted Vegetable Crop Production System on a Green Roof. *Acta Horticulturae*, 782.

Emilsson, T. & Rolf, K. (2005).
Comparison of establishment methods for extensive green roofs in southern Sweden. *Urban Forestry & Urban Greening*, 3, 103–111.

Fischer, G., Hizsnyik, E., Prieler, S., van Velthuizen, H., Wiberg, D. (2012).
Scarcity and Abundance of Land Resources: competing uses and the shrinking land resource base. *Worlds Within Reach: From Science To Policy - IIASA 40th Anniversary Conference 2012kk*. October 24-26 2012. Vienna, Austria.
https://pure.iiasa.ac.at/id/eprint/12216/ [2023-02-02].

Fixen, P., Brentrup, F., Bruulsema, T., Garcia, F., Norton, R., Zingore, S. (2015).
Nutrient/fertilizer use efficiency: measurement, current situation and trends. In: Drechsel et al. (red). *Managing Water and Fertilizer for Sustainable Agricultural Intensification*. Paris: International Fertilizer Industry Association. 1-30.

FLL (2018).
- *Green Roof Guidelines - Guidelines for the Planning, Construction and Maintenance of Green Roofs*. Bonn, Germany: Landscape Development and Landscaping Research Society e. V. (FLL).

Gao, Y., Shi, D., Levinson, R., Guo, R., Lin, C., Ge, J. (2017).
Thermal performance and energy savings of white and sedum-tray garden roof: A case study in a Chongqing office building. *Energy and Buildings*, 156, 343–359.

Gasperi, D., Pennisi, G., Rizzati, N., Magrefi, F., Bazzocchi G., Mezzacapo, U., Stefani, M. C., Sanyé-Mengual, E., Orsini, F., Gianquinto, G. (2016).

Towards Regenerated and Productive Vacant Areas through Urban Horticulture: Lessons from Bologna, Italy. *Sustainability*, 8, 1347.

Goldstein, B., Hauschild, M., Fernandez, J., Birkved, M. (2016). Testing the environmental performance of urban agriculture as a food supply in northern climates. *Journal of Cleaner Production*, 135, 984-994.

Gong, Y., Yin, D., Li, J., Zhang, X., Wang, W., Fang, X., Shi, H., Wang, Q. (2019). Performance assessment of extensive green roof runoff flow and quality control capacity based on pilot experiments. *Science of the Total Environment*, 687, 505–515.

Graceson, A., Hare, M., Hall, N., Monaghan, J. (2011). Characterising the mineral components of green roof growing media. *1 st National Green Roof Student Conference*, 2011, May 16 – May 17 2011, Sheffield, England. https://www.greenroofs.com/2011/02/17/the-1st-national-green-roof-student-conference-the-green-roof-centre-2/ [2023-02-02].

Graceson, A., Hare, M., Monaghan, J., Hall, N. (2013a). The water retention capabilities of growing media for green roofs. *Ecological Engineering*, 61, 328–334.

Graceson, A., Monaghan, J., Hall, N., Hare, M. (2014). Plant growth responses to different growing media for green roofs. *Ecological Engineering*, 69, 196–200.

Graceson, A., Monaghan, J., Hare, M. C. (2013b). Spatial Arrangements and Physical Properties of Granular Mineral Materials and Composted Green Waste in Green Roof Growing Media. *Acta horticulturae*, 1013, 147-152.

Grard, B. J.-P., Chenu, C., Manouchehri, N., Houot, S., Frascaria-Lacoste, N., Aubry, C. (2018). Rooftop farming on urban waste provides many ecosystem services. *Agronomy for Sustainable Development*, 38, 2.

Grard, B. J.-P., Manouchehri, N., Aubry, C., Frascaria-Lacoste, N., Chenu, C. (2020).
Potential of Technosols Created with Urban By-Products for Rooftop Edible Production. *International Journal of Environmental Research and Public Health*, 17, 3210.

Grard, B., Bel, N., Marchal, N., Madre, M. N., Castell, J-F. (2015).
Recycling urban waste as possible use for rooftop vegetable garden. *Future of Food: Journal on Food, Agriculture and Society*, 3, (1), 21-34.

Grimm, N, B., Faeth, S, H., Golubiewski, N. E., Redman, C. L. Wu, J., Bai, X., Briggs, J, M. (2012).
Global Change and the Ecology of Cities. *Science*, 319, 754-760.

GRO (2014).
The GRO Green Roof Code Green Roof Code of Best Practice for the UK 2014. Sheffield, UK: The Green Roof Organisation.

Gruda, N. (2012).
Current and Future Perspective of Growing Media in Europe. *Acta horticulturae*, 960, 37-43.

Gruda, N., Qaryouti, M. M., Leonardi, C. (2013).
Growing media. In: Baudoin, W., Nono-Womdim, R., Lutaladio, N., Hodder A., Castilla, N., Leonardi, C., De Pascale, S., Qaryouti, M. (eds.). *Good Agricultural Practices for greenhouse vegetable crops Principles for Mediterranean climate areas*. Rome: Food and Agriculture Organization of the United Nations. 271-301.

Harada, Y. & Whitlow, T. H. (2020).
Urban Rooftop Agriculture. Challenges to Science and Practice. *Frontiers Sustainable Food Systems*, 4, 76.

Harada, Y., Whitlow, T. H., Bassuk, N. L., Russell-Anelli, J. (2017).
Biogeochemistry of Rooftop Farm Soils. In: Lal, R. & Stewart, B. A. (eds.). *Urban Soils*. Boca Raton: CRC Press. 275-294.

Harada, Y., Whitlow, T. H., Templer, P. H., Horwarth, R. W., Walter, M. T., Bassuk, N. L., Russel-Anneli, J. (2018a).
Nitrogen Biochemistry of an Urban Rooftop Farm. Frontiers in Ecology and Evolution, 6, 153.

Harada, Y., Whitlow, T. H., Walter, M. T., Bassuk, N. L., Russell-Anelli, J., Schindelbeck, R. R. (2018b).
Hydrology of the Brooklyn Grange, an urban rooftop farm. *Urban Ecosystems*, 21, 673–689.

Kader, S., Chadalavada, S., Jaufer, L., Spalevic, V., Dudic, B. (2022).
Green roof substrates - A literature review. *Frontiers in Built Environment*, 8, 1019362.

Kazemi, F. & Mohorko, R. (2017).
Review on the roles and effects of growing media on plant performance in green roofs in world climates. *Urban Forestry & Urban Greening*, 23, 13–26.

Kong, A. Y. Y., Rosenzweig, C., Arky, J. (2015).
Nitrogen Dynamics Associated with Organic and Inorganic Inputs to Substrate Commonly Used on Rooftop Farms. Horticultural Science, 50 (6), 806-813.

Krawczyk, A., Domagała-Świątkiewicz, I., Lis-Krzyścin, A., Daraż, M. (2017).
Waste Silica as a Valuable Component of Extensive Green-Roof Substrates. *Polish Journal of Environmental Studies*, 26 (2), 643-653.

Kuoppamäki, K., Setäläa, H., Hagner, M. (2021).
Nutrient dynamics and development of soil fauna in vegetated roofs with the focus on biochar amendment. *Nature-Based Solutions*, 1, 100001.

Lehmann, S. (2014).
Low carbon districts: Mitigating the urban heat island with green roof infrastructure. *City, Culture and Society*, 5, 1–8.

Li, S-x., Qin, H-p., Peng, Y-n., Khu, S. K. (2019).
Modelling the combined effects of runoff reduction and increase in evapotranspiration for green roofs with a storage layer. *Ecological Engineering*, 127, 302–311.

Lott, D. E. & Hammond, V. E. (2013).
Water Wise Vegetable and Fruit Production. Lincoln: University of Nebraska – Lincoln extension, Institute of Agriculture and Natural Resources.
https://extensionpublications.unl.edu/assets/pdf/g2189.pdf [2023-02-02].

McIntyre, K. & Jacobsen, B. (2000).
The capillary and lateral Movement of Water in Soils. In: McIntyre, K. & Jacobsen, B (eds.). *Practical Drainage for Golf, Sportsturf and Hortic Horticulture*. Chelsea: Ann Arbor Press. 39-56.

Matlock, J. M. & D. Bradley Rowe, D. B. (2017).
Does Compost Selection Impact Green Roof Substrate Performance? Measuring Physical Properties, Plant Development, and Runoff Water Quality. *Compost Science & Utilization*, 25 (4), 231-241.

Molineux, C., Gange, A. C., Connop, S. P., Darryl J. Newport, D. J. (2015).
Using recycled aggregates in green roof substrates for plant diversity. *Ecological Engineering*, 82, 596–604.

Monterusso, M. A., Rowe, D. B., Rugh, C. L. (2005).
Establishment and Persistence of *Sedum* spp. and Native Taxa for Green Roof Application. *Horticultural Science*, 40 (2), 391-396.

Nasr, J., McRae, R., Kuhns, J. (2010).
Scaling up urban agriculture in Toronto-building the infrastructure. Toronto: Metcalf Food Solutions.
https://metcalffoundation.com/wpcontent/uploads/2011/05/scaling-urban-agriculture.pdf [2023-02-02].

Nektarios, P. A., Ischyropoulos, D., Kalozoumis P., Dimitrios Savvas, D., Yfantopoulos, D., Ntoulas, N., Tsaniklidis, G., Goumenaki, E. (2022).
Impact of substrate depth and fertilizer type on growth, production, quality characteristics and heavy metal contamination of tomato and lettuce grown on urban green roofs. *Scientia Horticulturae*, 305, 111318.

Oberndorfer, E., Lundholm, Bass, B., Coffman, R. R., Doshi, H., Dunnet, N., Gaffin, S., Köhler, M., Liu, K. K. Y., Rowe, B. (2007).
Green Roofs as Urban Ecosystems: Ecological Structures, Functions, and Service. *BioScience,* 57 (10), 823-833.

Olsson, V. (2015).

Local and regional food - perspectives from the south Baltic region of Sweden History, current state and future trends. Pp. 43-57. In: Petrenko, A. & Müller-Hanse, B (eds.). *Interdisciplinary perspectives on local and regional food in the South Baltic Region*. Kristianstad: Kristianstad University Press.

Ondono, S., Bastida, F., Moreno, J. L. (2014).

Microbiological and biochemical properties of artificial substrates: A preliminary study of its application as Technosols or as a basis in Green Roof Systems. *Ecological Engineering*, 70, 189–199.

Orsini, F., Gasperi, D., Marchetti, L., Piovene, C., Draghetti, S., Ramazzotti, S., & Bazzocchi, G., Gianquinto, G. (2014).

Exploring the production capacity of rooftop gardens (RTGs) in urban agriculture: the potential impact on food and nutrition security, biodiversity and other ecosystem services in the city of Bologna. *Food Security*, 6, 781–792.

Ouellette, N. A., Walters, S. A., Midden, K. S. (2013).

Fertility Management for Tomato Production on an Extensive Green Roof. *Journal of Living Architecture*, 1, (1), 1-14.

Pettersson Skog, A., Malmberg, J., Emilsson, T., Jägerhök, T., Capener, C-M. (2021).

Grönatakhandbok Växtbädd och Vegetation, Betong, Isolering och Tätskikt. 2 utg., Stockholm: Svensk Byggtjänst AB.

Proksch, G. (2011).

Urban Rooftops as Productive Resources Rooftop Farming versus Conventional Green Roofs. (Considering Research: Reflecting upon current themes in Architectural Research 2011). Detroit: Architectual Research Centers Consortium.

Reiners, S., Ketterings, Q. M., K.J. Czymmek, K. J. (2019).

Nutrient guidelines for vegetables. (Department of Animal Science Publication Series 2019:249). Ithaca: Cornell University - Department of Animal Science College of Agriculture and Life Science.
http://nmsp.cals.cornell.edu/publications/files/VegetableGuidelines2019.pdf [2023-03-19].

Richards, P. J., Farrell, C., Tom, M., Williams, N. S. G., Fletcher, T. D. (2015). Vegetable raingardens can produce food and reduce stormwater runoff. *Urban Forestry & Urban Greening*, 14, 646–654.

Richards, P. J., Williams, N. S. G., Fletcher, T. D., Farrell, C. (2017). Can raingardens produce food and retain stormwater? Effects of substrates and stormwater application method on plant water use, stormwater retention and yield. *Ecological Engineering*, 100, 165–174.

Rodríguez-Delfín, A., Gruda, N., Eigenbrod, C., Orsini, F., Giorgio Prosdocimi Gianquinto, G. P. (2017). Soil Based and Simplified Hydroponics Rooftop Gardens. In: Orsini, F., Dubbeling, M., de Zeeuw, H., Gianquinto, G (Eds.). *Rooftop Urban Agriculture*. Chwam: Springer. 61-83.

Satterthwaite, D., McGranahan, G., Tacoli, C. (2010). Urbanization and its implications for food and farming. *Philosophical Transactions of the Royal Society*, 365, 2809-2820.

Savi, T., Boldrin, D., Marin, M., Love, V. L., Andri, S., Tretiach, M., Nardini, A. (2015). Does shallow substrate improve water status of plants growing on green roofs? Testing the paradox in two sub-Mediterranean shrubs. *Ecological Engineering*, 84, 292–300.

Savi, T., Marin, M., Boldrin, D., Incerti, G., Andri, S., Nardini, A. (2014). Green roofs for a drier world: Effects of hydrogel amendment on substrate and plant water status. *Science of the Total Environment*, 490, 467–476.

Seto, K. C. & Ramankutty, N. (2016). Hidden linkages between urbanization and food systems. *Science*, 352, 943-945.

Shafique, M., Kima, R., Rafiq, M. (2018). Green roof benefits, opportunities and challenges – A review. *Renewable and Sustainable Energy Reviews*, 90, 757–773.

Sisco, L., Monzer, S., Farajalla, N., Bashour, I., Saoud, I. P. (2017).
Roof top gardens as a means to use recycled waste and A/C condensate and reduce temperature variation in buildings. *Building and Environment*, 117, 127-134.

Statens Jordbruksverk (2020).
Skörd av trädgårdsväxter 2019. Stockholm: Statistiska centralbyrån. https://jordbruksverket.se/download/18.341a6d7171e33d0f42cd2c7/1588852981361/JO37SM2001.pdf [2023-02-15].

Swiader, J. M. & Ware, G. W. (2002).
Producing Vegetable Crops. 5th ed. Danville: Insterstate publishers.

Tan, C. L., Tan, P. Y., Wong, N. H., Takasuna, H., Kudoc, T., Takemasa, Y., Lim, C. V. J., Chu, H. X. V. (2017).
Impact of soil and water retention characteristics on green roof thermal performance. *Energy and Buildings*, 152, 830–842.

Thomaier, S., Specht, K., Henckel, D., Dierich, A., Siebert, R., Freisinger, U. B., Sawicka, M. (2014).
Farming in and on urban buildings: Present practice and specific novelties of Zero-Acreage Farming (ZFarming). *Renewable Agriculture and Food Systems*, 30 (1), 43–54.

United Nations. (2017).
World population projected to reach 9.8 billion in 2050, and 11.2 billion in 2100.
https://www.un.org/en/desa/world-population-projected-reach-98-billion-2050-and-112-billion-2100 [2023-03-19].

United Nations. (2018).
68% of the world population projected to live in urban areas by 2050 says UN.
https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html [2023-03-19].

United States Department of Agriculture. (2018).
Effects on Soil Water Holding Capacity and Soil Water Retention Resulting from Soil Health Management Practices Implementation — A Review of the Literature Posted to the NRCS Soil Health Website as of 9/2016. *Soil Health Literature Review*, 03.

United States Department of Agriculture. (2012).
Vegetables 2011 Summary. Naional Agricultural Statistics, ISSN: 0884-6413. US Department of Agriculture: Washington DC.

United States Department of Agriculture. (1991).
United States Standards for Grades of Fresh Tomato.
https://www.ams.usda.gov/sites/default/files/media/Tomato_Standard%5B1%5D.pdf [2023-03-19].

Varela, A., Sandoval-Albán, A., Munoz, M., Gomez Gomez, A., Bogoya, J. M., Combariza, G. (2021).
Evaluation of green roof structures and substrates for Lactuca sativa L. in tropical conditions. *Urban Forestry & Urban Greening*, 60, 127063.

Voeten, J. G. W. F., van de Werken, L., Newman, A. P. (2016).
Demonstrating the Use of Below-Substrate Water Storage as a Means of Maintaining Green Roofs – Performance Data and a Novel Approach to Achieve Public Understanding. In: Pathak, C. S. & Reinhart, D. (eds.). *World Environmental and Water Resources 2016: Professional Development Innovative Technology, International Perspectives and History and Heritage* May 22-26, West Palm Beach, USA. 12-21.

Walters, S. A. & Midden, K. S. (2018).
Sustainability of Urban Agriculture: Vegetable Production on Green Roofs. *Agriculture*, 8, 168.

Wang, J., Garga, A., Huang, S., Mei, G., Liu, J., Zhang, K., Gan, L. (2021).
The rainwater retention mechanisms in extensive green roofs with ten different structural configurations. *Water Science & Technology*, 84, 8, 1840.

Whittinghil, L. J. & Rowe, D. B. (2012).
The role of green roof technology in urban agriculture. *Renewable Agriculture and Food Systems*, 27, 4, 314–322.

Whittinghill, L. J., Bradley Rowe, D. B., Cregg, B. M. (2013).
Evaluation of Vegetable Production on Extensive Green Roofs. *Agroecology and Sustainable Food Systems*, 37:4, 465–484.

Whittinghill, L. J. & Poudel, P. (2020).
Yields of relay cropped greens grown in grown in green roof production systems. (Urban Food Systems Symposium: Nourishing Cities in a Changing Climate 2020). Manhattan: New Prairie Press.

Whittinghill, L. J., Hsueh, D., Culligan, P., Plunz, R. (2016a).
Stormwater performance of a full scale rooftop farm: Runoff water quality. *Ecological Engineering*, 91, 195–206.

Whittinghill, L. J., Rowe. D. B., Ngouajio, M., Cregg, B. M. (2016b).
Evaluation of nutrient management and mulching strategies for vegetable production on an extensive green roof. *Agroecology and Sustainable Food Systems*, 40:4, 297-318.

Whittinghill, L. J. & Starry, O. (2016).
Up on the Roof: Considerations for Food Production on Rooftops. In: Brown, S., McIvor, K., Hodges Snyder, E. (eds.). *Sowing Seeds in the City Ecosystem and Municipal Services*. Dordrecht: Springer. 325-339.

Appendix 1

Table 1. Scientific parameters for URTA-crop[100] evaluation

STUDY	PARAMETER
Cho et al. 2008	Shoot fresh weight (g), shoot dry weight (g)
Dorr et al. 2017	Yield: kg/m^2
Elstein et al. 2008	Dry weight (g)
Eksi et al. 2016	Plant growth index, clorophyll fluorescence value, root dry weight (g), shoot dry weight (g), total dry weight (g), root-shoot ratio
Grard et al. 2018	Food supply/food production: kg/m^2
Grard et al. 2020	Yield: kg/m^2
Orsini et al. 2018	Yield: kg/m^2
Nektarios et al. 2022	Growth rate index (cm), total production (g/plant), dry weight (g), water content (% w/w), fruit firmness (kg), total soluble solids (Brix degrees)
Sisco et al. 2017	Leaf weight (g), root length (cm), root weight (g), total leaf biomass (g), total root biomass (g), total weight (g)
Varela et al. 2021	Plant height (cm), root length (cm), yield (g/cm^2)
Whittinghill et al. 2013	Total yield (g), yield (g/plant), marketable yield (g), marketable yield (%), number of fruit (n), biomass wet weight (g), marketable biomass (%), fruit size (cm), fruit color, fruit grade
Whittinghill et al. 2016b	Yield (g/plant), total yield (g), biomass fresh weight (g), fruit grades (USDA 1991)

---

[100] Leafy vegetables and tomatoes.

Appendix 2

Terminology

Aeration: movement and exchange of air within a soil.

Aggregate: soil units formed by connections of particles, created by positively charged cations enabling negatively charged soil particles to join.

Aquifuge: a mass/material blocking water transportation.

Cation Exchange Capacity (CEC): a soil’s total amount of negative charges that can bind exchangeable cations. These ions are easily accessible for plant metabolism and are protected from leaching.

Colloids: small soil particles with a large surface area to volume ratio, important for SGM-nutrient retention.

Dry bulk density: the weight of a dry soil divided by its volume.

Field capacity: the amount of retained water in soil, once free water[101] has been drained.

Internal pore: cavity within a particle.

Organic Matter (OM): material made up of carbon compounds formed by living organisms, such as plant decay and animal feces.

---

[101] Water at null suction (McIntyre and Jacobsen 2000).

Mulch: material covering the soil.

Particle-size distribution: the amount of different particle sizes within a given soil. Usually expressed as weight percentages.

Pore-size distribution: the volume of different pore sizes within a given soil. Expressed as percentage of total soil volume.

Plant Available Water (PAW): the amount of water stored in soil available for plant uptake. This is equivalent to the amount of water held in pores between the boundaries of field capacity and wilting point[102].

Pore: cavity between particles.

Saturated bulk density: the weight (g) of a fully soaked soil divided by its volume (cm^3).

Substrate/Growing Media (SGM): "all those solid materials, other than soil, which alone or in mixtures can guarantee better conditions than agricultural soil (for one or more aspects)." (Gruda et al. 2013: 271).

Urban Rooftop Agriculture (URTA): a form of urban agriculture, where food is grown on top of buildings in cities.

Water Holding Capacity (WHC[103]): the ability of a certain soil texture to hold water against gravity.

---

[102] The amount of water which is needed for plant survival. Beyond this point, plants wilt and cannot recover.

[103] WHC and water retention seem to be used synonymously. The USDA (2018:4) refers to water retention as: "the actual amount of water retained in the soil for crop use". In this study the phenomenon is referred to as WHC.

Publishing and archiving