Soil-less systems vs. soil-based systems for cultivating edible plants on buildings in relation to the contribution towards sustainable cities

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Abstract

Food production and consumption for cities has become a global concern due to increasing numbers of people living in urban areas, threatening food security. There is the contention that people living in cities have become disconnected with food production, leading to reduced nutrition in diets and increased food waste. Integrating food production into cities (urban agriculture) can help alleviate some of these issues. Lack of space at ground level in high-density urban areas has accelerated the idea of using spare building surfaces for food production. There are various growing methods being used for food production on buildings, which can be split into two main types, soil-less systems and soil-based systems. This paper is a holistic assessment (underpinned by the triple bottom line of sustainable development) of these two types of systems for food production on buildings, looking at the benefits and limitation of each type in this context. The results illustrate that soil-less systems are more productive per square metre, which increases the amount of locally grown, fresh produce available in urban areas. The results also show that soil-based systems for cultivation on buildings are more environmentally and socially beneficial overall for urban areas than soil-less systems.

Introduction

Urbanisation has resulted in more than half of the world's population living in cities. For the first time in history, in mid-2009 the world's population has become more urban than rural (R. C. Allen, 2009). Urban areas rely on external resources to function, including food, water and energy, where this reliance makes cities global risk areas for human habitation (Kraas, 2003) due to issues that could occur in the supply chains (e.g. food security where there is a risk that people are no longer able to access healthy food easily (FAO, 1996)) and in parallel to this, due to issues with unhealthy urban environments that degrade people's health and quality of life. Increasingly people have become interested in reducing this reliance by re-integrating the production of resources in cities, including producing food (urban agriculture). Creating healthier places for people (and other creatures) to live in is also on top of the agenda for the future sustainability of cities where the importance of green spaces and infrastructure has been highlighted (Kirby & Russell, 2015). Green infrastructure also increases biodiversity in urban areas (Newton, Gedge, Early, & Wilson, 2007). The benefits of continuous pockets of spaces for wild life inspired the "My Wild Street" project in Bristol, UK where front gardens in a dense urban street were transformed into havens for wildlife (WT, 2015).

Integrating green spaces and vegetation into urban areas also helps cities function more efficiently and sustainably by: helping the retention of storm water to contribute to sustainable urban drainage (Sheweka & Magdy, 2011), purifying air pollution (Ottele, van Bohemen, & Fraaij, 2010) and shading hard surfaces to help alleviate

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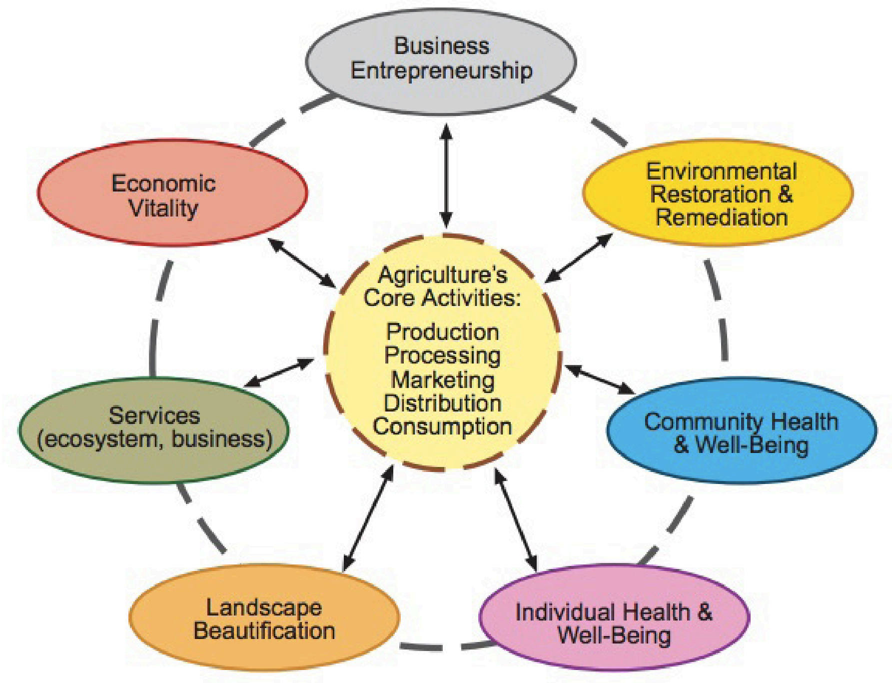

Figure 1: Diagram from the USA's Council for Agriculture, Science and Technology representing urban agriculture as a system (Butler & Maronek, 2002, p. 14)

the urban heat island effect (Mavrogianni et al., 2009)

There is the contention that if people are more involved with food production it will help improve their diets (J. O. Allen, Alaimo, Elam, & Perry, 2008; Benton, 2014; Kortright & Wakefield, 2011; Lovell, 2010; Wakefield, Yeudall, Taron, Reynolds, & Skinner, 2007) and also increase their pro-environmental behaviour (Mayer & Frantz, 2004) such as reducing the food that they waste (Benton, 2014). The definition of urban agriculture from the USA's Council of Agriculture, Science and Technology is:

> Urban agriculture is "a complex system encompassing a spectrum of interests, from a traditional core of activities associated with production, processing, marketing, distribution, and consumption, to a multiplicity of other benefits and services that are less widely acknowledged and documented. These include recreation and leisure activities, economic vitality and business entrepreneurship, individual health and well-being, community health and well-being, landscape beautification, and environmental restoration and remediation." (Butler & Maronek, 2002, p. 6)

The definition above is illustrated in **Figure 1**, which is a summary of the benefits urban agriculture can give to cities.

In dense urban areas, land for urban agriculture and green spaces are in competition with land for buildings (offices/housing etc.), so people are increasingly integrating food production and green spaces within and on buildings (Delor, 2011; Despommier, 2011). Vertical farms (Despommier, 2011) and building integrated agriculture (Delor, 2011) look at using internal spaces to grow food on and within buildings. Spare building surfaces such as rooftops, walls, windowsills and balconies have also been used for food production. There are various cultivation systems that can be used for cultivating food on buildings. These systems can be split into two types: soil-less systems and soil-based systems. Both types of systems can be in open air or within enclosed spaces using natural light in greenhouses and/or artificial light in warehouse type spaces. This paper is an assessment of these two types of systems in relation to cultivating edible plants on buildings.

Methods

In this paper, soil-less and soil-based systems for cultivating food on buildings have been assessed using specific criteria relevant to an urban context and a building context, underpinned by the environmental, social and economic discussions above. This section of the paper will explain the choice of criteria and their relevance.

Choice of criteria

Each criterion is split into three categories which are the triple bottom line of sustainable development (environmental, social and economic (Elkington, 1994)). The criteria are based on the benefits that these systems can contribute towards the sustainability of cities. The criteria are shown in **Table 1**.

Table 1 (a) : Explanation of assessment criteria chosen for comparing soil-less systems and soil-based systems for cultivating edible plants on buildings in relation to their contribution towards creating sustainable cities - **Environmental**

Criterion	Explanation of relevance
Environmental	
Can contribute to sustainable urban drainage	Hard surfaces in urban areas are not able to absorb water, thus during heavy rainfall, urban drainage systems are under pressure to drain water away, which can lead to flash floods and/or mixing of storm water with sewage, thus sustainable urban drainage (SUD) strategies try to slow down water from heavy rain before it enters drains (DEP, 2010). Thus the ability for water retention of the systems will be assessed.
Can contribute to alleviating the urban heat island effect	The urban heat island effect is a phenomenon where urban temperatures are a few degrees hotter than their surrounding rural areas due to an increase in hard surfaces that absorb heat in combination with air pollution creating a mini greenhouse effect (EPA, 2012). Vegetation in urban areas can help create surfaces that reflect heat and provide shade (Mavrogianni et al., 2009). The ability of the systems to help alleviate the above will be assessed.
Ease of using organic fertiliser from urban waste streams	Cities produce a lot of organic waste that can be utilised for cultivation rather than sent to landfill sites. Methods of cultivation within cities can tap into these waste streams as a source of organic fertiliser for the plants (Garner & Keoleian, 1995). The ability for each system type to be able to do this will be assessed.
Contribution to biodiversity	Spaces for biodiversity are important for healthy urban areas for humans and other creatures, flora and fauna (Francis & Lorimer, 2011). Green spaces integrated on buildings can help contribute to biodiversity in urban areas (Newton et al., 2007). The systems will be assessed in relation to the above.
Water efficiency	The efficient use of water is becoming increasingly important due to water scarcity in many parts of the world and especially in urban areas (Lee, Jordan, & Coleman, 2014; WFN, 2012). Products, including crops, have a water footprint, which is the amount of embodied water used in their production. Thus water efficiency of systems for cultivating edible plants on buildings is important and will be assessed for each system type.
Waste water is a pollutant to ecosystems and groundwater	As with industrial agriculture, the wastewater from systems for cultivating edible plants on buildings should be managed effectively in order to prevent the pollution of groundwater with excess minerals (Kumar & Cho, 2014). This will be assessed for each system type
Visual amenity	Plants are seen as visually appealing, thus integrating plants on buildings can increase the visual amenity of places. Soil-less and soil-based systems will be given a score related to their visual amenity.
Highly impacted by urban air pollution	Studies have shown that crops can take up pollutants in urban environments such as trace metals, which are damaging to human health (Säumel et al., 2012). Soil-less and soil-based systems will be scored according to their vulnerability to this issue.
Specialist nutrient solution not needed in order to achieve nutrient rich produce	Crops grown in soil using organic methods are nutritionally superior to crops grown inorganically in soil using chemical fertilisers (SA, 2015). Soil-less and soil-based systems will be scored according to achieving crops that are high in nutrition.
Reliance on fossil fuels for energy	Due to climate change (IPCC, 2007) and peak oil (ASPO, 2010), the use of fossil fuels for energy has become a global issue. Soil-less and soil-based systems for cultivating edible plants on buildings will be scored according to their energy in usage.
Embodied energy	Soil-less and soil-based systems will be scored according to their embodied energy in manufacturing and transporting of parts and embodied energy of products brought in during cultivation.
Reliance on back-up energy supply in case of power outages	A cultivation system that is reliant on a source of energy for the plants to survive is reliant on a back-up energy supply. Soil-less and soil-based systems will be scored according to whether they need a back-up energy supply.
Can grow crops in a range of climatic conditions	Methods for cultivation on buildings can be affected by climatic conditions due to loss in productivity and/or higher risk of disease (Orsini, Kahane, Nano-Womdim, & Gianquinto, 2014).
Soil as a finite resource	Soil is seen as a finite resource that needs to be managed sustainably in order to feed the growing world population and contribute to reducing greenhouse gas emissions (FAO, 2015). Soil-less and soil-based systems will be scored against how they would contribute to this issue.
Reconnecting with the natural world	People who live in cities are disconnected with nature. Connecting with the natural world is important for increasing pro-environmental behaviour (Mayer & Frantz, 2004). Soil-less and soil-based systems will be scored according to how they can reconnect people with nature.

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Table 1 (b) : Explanation of assessment criteria chosen for comparing soil-less systems and soil-based systems for cultivating edible plants on buildings in relation to their contribution towards creating sustainable cities - **Social**

Criterion	Explanation of relevance
Social	
Amount of knowledge needed in order to produce nutritionally rich crops.	There is a lack of horticultural knowledge amongst people who live in cities (FLP, 2010). Soil-less and soil-based systems will be scored according to the level of knowledge needed to grow good quality crops.
Social acceptance	Cultivation in urban areas in general may not be socially accepted due to issues with pollution uptake. Soil-less and soil-based systems will be scored according to their social acceptance.
Resilience to neglect	Neglect is an issue due to the transient nature of urban populations. Soil-less and soil-based systems will be scored according to their resilience under neglect.
Provides an amenity space for urban dwellers	Amenity space is important in urban areas for the physical and mental health of urban dwellers (NA, 2010). Soil-less and soil-based systems will be scored according to their contribution to amenity space.
Increasing access to affordable, fresh produce	Productivity levels of cultivation systems become important when the aim is to produce as much local, fresh produce as possible for urban dwellers in order to improve diets. This is often the case in poorer urban areas where people are not able to easily access fresh produce due to transport limitations to larger food retailers (food deserts) (Viljoen, 2005). Soil-less and soil-based systems will be scored according to how well they empower people to have access to fresh produce.

Table 1 (c) : Explanation of assessment criteria chosen for comparing soil-less systems and soil-based systems for cultivating edible plants on buildings in relation to their contribution towards creating sustainable cities -**Economic**

Criterion	Explanation of relevance
Economic	
Productivity	Soil-less and soil-based systems will be scored according to their productivity per square metre.
Cost to start up in comparison to each other	The cost of start up for each system is important and initial capital available can affect the type of growing system that can be used.
Cost to maintain in comparison to each other	The cost of maintenance for each system is important as the garden should be able to work financially.
Weight	The weight of each system type will be compared. Weight is an important factor due to structural limitation on buildings.
All types of crops can thrive in the system	The system types will be compared in relation to the types of crops that grow productively in the systems. There is more flexibility for the grower if they can grow a large variety of crops.

Each system will be given a score out of 3 for each criterion discussed in **Table 1** below, where a score of 0 means that the system is not able to meet this criterion at all, 1 means the system is able to meet this criterion in part, 2 means the system is able to meet this criterion but at a higher effort in general (effort is assessed according to cost, maintenance time and level of knowledge needed to achieve this benefit) and 3 means the system is able to meet this criterion very easily. The scores will be shown in brackets throughout the sections below. An example is given below of one criterion and how the scores were given:

Water Efficiency: Soil-less system is scored 3 as they can loop water around the system (more explanation of this in the sections below). Soil-based systems are scored 2 as they can be very water efficient but specialist knowledge is needed to make a soil-based system that is very water efficient. The scoring system in this paper is limited as the amount of specific details available for cost, maintenance time and level of knowledge are not specified, but are designed to give a general idea for each system type. The scoring system in this paper is limited as the amount of specific details available for cost, maintenance time and level of knowledge are not specified, but are de-

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Table 2 : Examples of soil-less cultivation of food on buildings

Name	Gotham Greens, Greenpoint	Sun works roof-top greenhouse	Rooftop Garden	Arbor House, Sky Vegetables	UrbanFarmers AG	Window farms
Location	Brooklyn, New York, USA	Manhattan School, New York, USA	Bologna, Italy	Bronx, New York, USA	The Hague, Netherlands, Rooftop and 6th Floor	N/A
Type	Hydroponic rooftop greenhouse	Hydroponic and soil based rooftop greenhouse	Hydroponic and soil-based	Hydroponic rooftop greenhouse	Rooftop Aquaponics	Indoor vertical window hydroponic systems
Funding	Private	State	Research	State	Private	Private
Commercial/ Community/ Educational/ Individual	Commercial	Educational	Research project	Commercial/Educational	Commercial/Educational	Individual
Year built	2010	2010	2014	2013	Construction due to finish in 2016	N/A
Size (m²)	1393 (GothamGreens, 2015)	Unknown	216 (Orsini, Gasperi, et al., 2014)	743 (Wall, 2013)	1200 total: 330 vegetables and fruit growing, 370 fish farm, 250 processing and packaging and 250 events and tours (HD, 2015)	1-May
Controlled environment (lighting, temperature and humidity)	Yes	Yes	No	Yes	Yes	No
Irrigation	Pump irrigation system	Pump irrigation system	Pump irrigation system	Pump irrigation system	Pump irrigation system	Pump irrigation system
Nutrients used	Water soluble mineral salts and micronutrients (Loria, 2015)	Various including water soluble mineral salts and micronutrients and vermiculture solutions	Water soluble mineral salts and micronutrients and soil with granular fertiliser once per year	Water soluble mineral salts and micronutrients	Nutrients from fish	Water soluble mineral salts and micronutrients
Productivity (kg/m²/year)	65 (GothamGreens, 2015)	N/A	15-Feb	Unknown	Unknown	Low (Gorgolewski, Komisar, & Nasr, 2011)
Crops grown	Salads, leafy herbs and tomatoes	Kale, Arugula, basil, broccoli, beets, cabbage and lettuce (NYSW, 2011)	Cantaloupe, tomato, chilli pepper, eggplant, lettuce, watermelon, chicory, black cabbage	Greens and herbs like lettuce, kale and basil (Wall, 2013)	Unknown	Salads and leafy herbs
Cost (per m²)	$574 (Pasquarelli, 2014)	Unknown	Unknown	Unknown	Unknown	$70 if using plastic bottles for a two-column system to $280 for a two-column ready made kit.

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signed to give a general idea for each system type.

Soil-less systems for cultivating edible plants on buildings: evaluation of benefits related to and contribution towards more sustainable cities

Soil-less systems for cultivating edible plants on buildings use horticultural technologies called hydroponics (mineral nutrient solution instead of soil), aeroponics (nutrient mist) or aquaponics (nutrient solution from tanked fish). **Table 2** shows some examples of soil-less systems. Removing soil from the growing process means that nutrients can be directly given to the plant roots, which speeds up their growth rate, making yields much higher (4 times more (Jenkins, Keeffe, & Hall, 2015)) than growing in soil under the same conditions (Muro, Diaz, Goni, & Lamsfus, 1997) (Score 3 for Productivity). These productivity levels make soil-less technologies a profitable and financially viable form of cultivating edible plants on buildings as there is more yield per square metre (Wilson, 2002). The productivity levels also mean that these systems can reduce the carbon footprint of cities in relation to food due to reduced food miles (Astee & Kishnani, 2010). Some crops are not as productive in soil-less systems than others and thus do not make financial sense to grow in a soil-less system (Score 2 for crop types).

Soil-less systems use water in two different ways; they either recirculate the water continuously around the system or run the nutrient solution through the system once and dispose of the water (run-to-waste). By circulating the nutrient solution within a closed system, hydroponics can use 4 times less water compared to the same yield from industrial field agriculture (Astee & Kishnani, 2010) (Score 3 for water efficiency). Periodic samples of the water used in a hydroponic system should be tested in order to monitor the build up of toxins in the system and other indicators such as the PH of the water.

Both systems will eventually lead to the need to dispose of wastewater. The waste solution can pollute ecosystems and groundwater (Kumar & Cho, 2014) thus needs to be treated before entering waste water systems. Recirculating systems use less water and also produce less wastewater so they would work better in an urban setting (Score 2 for pollution in wastewater).

Soil-less systems use electric pumps to circulate water to the plant roots, so are reliant on a source of energy to function. This can be partly supplied by renewable technology which is demonstrated on The Science Barge in New York, USA (Nelkin & Linsley, 2009). This use of electricity increases the embodied energy of crops grown in hydroponic systems (protective cropping, such as greenhouses, can carry approximately 84% higher emissions, due to heating, lighting and the structures themselves (Denny, 2014)) in comparison to locally grown soil-based crops, thus the use of renewable energy sources is beneficial in order to reduce this embodied energy and reliance on fossil fuels of soil-less systems.

The use of renewable energy may affect the economic sustainability of a soil-less system (Score 2 for Reliance on fossil fuels). A back up of energy should be installed for soil-less systems as power outages of even a few hours can destroy an entire crop in the system as the roots do not have a buffer (such as soil) to stay alive (Score 2 for back up energy supply). **Table 2** shows that most soil-less systems have been designed under controlled environments (also known as protected cropping) such as greenhouses. This may be because soil-less systems can produce higher yields under controlled environments where the lighting and temperature can be controlled creating the possibility to grow food all year. One negative affect of this is the added weight of the system if glass is used (the weight could be reduced by using translucent plastic, although the aesthetics of this would need to be considered carefully as urban greenhouses would be highly visible by urban dwellers) (Score 2 for weight). Growing spaces in controlled environments also do not provide the visual amenity benefits (which in turn has health benefits (Kirby & Russell, 2015; Ulrich, 1984)) of integrating green spaces and infrastructure in dense urban environments if the plants are not visible to city dwellers. A view of vegetation may be more valuable in dense urban areas than a view of a greenhouse.

Another negative affect of this is that putting the plants under controlled environments means that the biodiversity benefits obtained from growing the plants in an urban setting are no longer achieved. Soil-less systems grown in open air are not as productive as systems in controlled environments, but they are able to contribute to biodiversity for more mobile species in urban areas such as bees and butterflies (Score 1 for contribution to biodiversity). Open-air soil-less systems would also provide exposed vegetation thus increasing vegetated surfaces in urban areas, which helps alleviate the urban heat island effect (Score 1 for alleviating urban heat island). An advantage of growing in controlled environments in urban areas is that it reduces the pollution uptake of the crops as they aren't exposed to air pollution and other sources of pollution from an urban setting (Score 3 for pollution uptake).

Soil-less systems can also produce nutrient comparable or superior crops, compared with soil-grown crops, with precise nutrient solutions used and stringent management of the system undertaken (Hayden, 2006). The right nutrient solution and knowledge can be difficult for growers to access, especially in low-income situations such as in economically developing countries (Orsini, 2014b). Issues with achieving good nutritional content in soil-less systems has led to these systems sometimes not being as socially accepted as soil-based systems (Specht et al., 2014) (Score 1 for social acceptance).

Organic water-soluble nutrient solutions can be used in hydroponic systems, such as vermiculture produced from food waste, where the nutrient content of these solutions should be checked regularly and supplemented with other water-soluble organic materials in order to achieve comparable or superior nutrient content in crops compared with soil-based systems (Wilson, 2002) (Score 2 for nutrients in crops). Mineral nutrient solutions are less time consuming to use in order to achieve successful results, but the nutrients are mined (sometimes from non-renewable sources), refined and imported (sometimes from long distances), which increases the embodied energy and ecological footprint of the final crops (Score 1 for embodied energy). The use of specialist equipment also increases the embodied energy and start up costs (Score 1 for start up costs).

Aquaponics are also a solution for a less energy intensive source of nutrients, where waste-water from tanked fish is used to feed the plants. The external source of nutrients in an aquaponics system is the food for the fish. This can be home made, but similar to hydroponics nutrients, they need to be carefully formulated to ensure there is a balance of nutrients for the plants and the fish (TAS, 2015). The nature of needing specially formulated nutrients for hydroponic and aquaponic systems provides a potential business opportunity to supply local, organically formulated products to sell to growers (Score 1 for organic fertiliser). A negative effect of this is that specialist knowledge is needed to grow edible plants in a soil-less system in order to yield nutrient rich crops, thus this may socially exclude urban dwellers who don't have this knowledge and/or the financial resources to pay for the materials needed (Specht et al., 2015) (Score 1 for specialist knowledge needed). This requirement may impact on inspiring garden visitors who may like to replicate a growing system on a building surface of their home but may feel that they do not have the specialist knowledge to do it. Soil-less systems may be more appealing to technically orientated people where they feel they are in more control of their planting system. It could be argued that the world's population is becoming increasingly more technically orientated due to the increased use of computing technology. It could also be argued that inspiring urban dwellers to grow food using high-tech systems could disconnect them further from the natural world and an understanding of how our actions impact the planet (Score 1 for reconnecting with the natural world).

The specialist equipment, staff and energy needed to cultivate crops using soil-less systems also means that the prices of crops may not be affordable without subsidy for poorer communities in urban areas, who are vulnerable in terms of easy access to affordable fresh produce and have higher rates of obesity (ibid) (Score 2 for easy access to fresh produce). Small-scale hydroponic systems have been designed for domestic use where common waste products can be used to set up the system, but they produce small quantities of food (Gorgolewski et al., 2011), which negates one of the key benefits of using a hydroponic system (productivity). Soil-less systems for cultivating edible plants on buildings contribute to sustainable urban drainage if rainwater collection from surface run-off is designed into the system. This is a requirement for rooftop greenhouses in New York City, USA (NYCDCP, 2012) (Score 2 for SUDs). Water can be stored on the building (although this would add extra weight to the structure) or stored at ground level and pumped back up.

Soil-less systems are not as socially accepted as soil-based systems as they are a technology that people are not familiar with (Specht et al., 2014), and where they may not be sure about the quality of the crops (Gorgolewski et al., 2011). **Table 2** highlights that soil-less systems for cultivating edible plants on buildings are a concept that have very recently become reality, thus there aren't many examples showing their success in practice, but there is confidence that they could work (Score 1 for social acceptance). Any crop could be grown in a hydroponic system but some produce higher yields than others (Loria, 2015; Orsini, Gasperi, et al., 2014) (Score 2 for types of crops). Soil-less systems that use a nutrient solution as the substrate cannot function above certain temperatures due to reduced concentration of oxygen in the nutrient solution (Orsini, Kahane, et al., 2014). These systems are also not recommended in areas where diseases can be spread by mosquitoes (ibid). Soil-less systems that use specially designed substrates do not have the issues above.

Due to the high productivity levels of soil-less systems, they could be used in rural areas to replace some areas of industrial soil-based farming in order to give the soil time to restore its fertility (Vogel, 2008). In an urban context, soil-less systems for cultivation on buildings could be used where it is difficult to access clean urban soil to put on the building (Score 2 for soil as a finite resource). Soil-less systems are not able to function if they are neglected. The system will stop performing its function to produce food, and other functions. This highlights the

Figure 2: Food Chain, LA, USA, Edible Vertical wall (GR, 2008)

importance of soil-less systems to be set up with a resilient business plan to ensure the success of the system. If a household decides to set-up a soil-less growing system rather than a soil-based growing system, they will need to consider who will look after their plants when they are away from home (e.g. on holiday), as it would not be as simple as the neighbours coming to water the plants, although it could be simple if they arrange for a specialist company to look after their plants (Score 1 for resilience to neglect).

Soil-less systems are not able to be in the form of green, amenity spaces without the loss of productive space as they need specialist knowledge and monitoring to operate successfully, thus visitors need to come at allocated times and for allocated tasks. In dense urban areas, productive green spaces that can also be amenity spaces are a valuable contribution to creating healthy cities. This highlights a potential area for further research, where it can be assessed how soil-less systems could also perform as amenity spaces for urban dwellers without the loss of productivity (Score 2 for amenity space). The maintenance costs are higher for soil-less systems on buildings, as more monitoring is required from specialist staff and nutrients are more costly (Score 2 for maintenance costs).

Soil-based systems for cultivating edible plants on buildings: evaluation of benefits related to and contribution towards more sustainable cities

Soil-based systems for cultivating edible plants on buildings are systems that integrate soil, compost or specially designed lightweight soil-based growing medium on building surfaces or within buildings. This is essentially growing crops in containers (large containers in the case of an intensive green roof, and container systems designed for mounting to walls in the case of edible vertical walls (**Figure 2**) where the containers are on the surface of a building.

Table 3 shows examples of soil-based systems. As well as the soil retaining water, containers for growing food on buildings can be designed with water-reservoirs to retain some water within the system for times of drought. The drainage layer is important for both holding water and draining it away from the building surface. Soil-based systems contribute to sustainable urban drainage as they can retain storm water and release it gradually (Score 3 for SUDs). The irrigation systems for soil-based systems are similar to growing in soil at ground level (hand-watering, automatic pumps with irrigation pipes, seep hoses etc.) (Score 2 for water efficiency).

The source of nutrients for soil-based systems are within the growing medium and need to be replenished every few weeks, depending on the type of growing medium, during the peak of a growing season for fruiting crops and fully replenished annually; similar to growing in soil at ground level and far less seldom than soil-less systems. Artificial fertilisers can be used as well as organic fertilisers. As with soil-less systems but with less technical expertise required, soil-based systems can utilise the urban waste streams and use composted food and green waste as a source of nutrients to replenish the containers (Grard et al., 2015).

For intensive green roofs or larger containers, mulching practices can be used at the beginning of the growing season, such as mulching with matured horse manure

Table 3 : Examples of soil-based cultivation of food on buildings

Name	Eagle Street Rooftop Farm	Food Chain, Skid Row Housing Trust	Brooklyn Grange, Flagship farm	RISC Roof Garden	Gary Comer Youth Center
Location	Brooklyn, New York, USA	Los Angeles, USA	New York, USA	Reading, UK	Chicago, USA
System type	Green roof	Green wall	Green roof	Green roof	Green roof
Type of growing medium	Rooflite (compost, rock particulates and shale) (Gorgolewski et al., 2011)	BioSoil (soil specially formulated beneficial bacteria) (Irwin, 2012)	Rooflite (compost, rock particulates and shale) (Gorgolewski et al., 2011)	Soil	Soil
Funding	Private	Private	Private	Charity	Private
Commercial/ Community/ Individual	Community/Educational	Community	Commercial	Educational	Community/Educational
Year built	2009	2008	2009	2002	2006
Size (m²)	560	17 (GR, 2008)	3994	200 (Richards, 2008)	760 (Gorgolewski et al., 2011)
Controlled environment (lighting, temperature and humidity)	No	No	No	No	No
Irrigation	Hand watering	Pump irrigation system	Seep hoses from mains water	Hand-watered from mains water	Rainwater collection and mains water by hand a seep hoses (Gorgolewski et al., 2011)
Nutrients used	Compost	Compost	Compost	Compost	Compost
Productivity (kg/m²/year)	Unknown	Unknown	6.1 (Brooklyn-Grange, 2015)	Unknown	0.6 (Gorgolewski et al., 2011)
Crops grown	Cucumbers, hot peppers, tomatoes, eggplants, spinach, radishes, kale, swiss chard, carrots, peas, beans, salad greens (lettuces, mustards, arugula) herbs (sage, tarragon, oregano, parsley, chives, cilantro, dill), flowers (cosmos, zinnias, calendula, tobacco, daisys, hops) corn and squash (ESRF, 2010)	Tomatoes, cucumbers, strawberries, bell peppers, hot peppers, tomatillos, spinach, parsley, leeks, edible lavender, eggplant, zucchini, Sugar Baby watermelon, a variety of herbs, lettuce varieties, radish, and legumes (GR, 2008)	Leafy greens, tomatoes, peppers, kale, chard, chicories, ground cherries, eggplants, pac choi, herbs, carrots, turnips, radishes, beans (Brooklyn-Grange, 2015)	185 species of plants (RISC, 2015)	Variety including cabbages, lettuces, carrots, sunflowers and strawberries (Gorgolewski et al., 2011)
Cost (per m²)	$10 (Gorgolewski et al., 2011)	Unknown	$5 (Gorgolewski et al., 2011)	Unknown	Unknown

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or compost made from food and garden waste (Richards, 2008) (Score 3 for nutrients in crops). Growing in soil-based systems on buildings needs similar gardening skills required for growing at ground level in a garden. This makes soil-based systems accessible to a higher number of urban dwellers due to the less technical knowledge needed (Score 3 for specialist knowledge needed) and the lower cost of the materials required. Due to the basic knowledge that is required for this method of cultivation, food production in soil can help empower local communities to take control of the food that they eat by demonstrating how they could grow their own food (Lovell, 2010). Growing in soil is similar to how plants grow in the natural world thus when growing in soil, people are reconnecting with nature and increasing their understanding of natural systems (Score 3 for reconnecting with nature).

Some soil-based systems can also require high initial investment costs if any of the following are required; the building surface needs to be structurally reinforced, access needs to be created to the building surface, if an intensive green roof and/or other things (such as sheltered space). **Table 3** shows that the cost to start up soil-based systems on buildings are much less than soil-less systems (Score 2 for start up costs). Most soil-based systems for cultivating edible plants on building have been designed as open-air systems, which can provide valuable biodiversity corridors within dense urban areas for many different types of flora and fauna (Dunnett, Nagase, & Hallam, 2008) (Score 3 for contribution to biodiversity). Open-air soil-based systems also help alleviate the urban heat island effect by increasing the amount of vegetated surfaces in urban areas (Score 3 for alleviating urban heat island). Vegetable gardens can also be used as amenity spaces without needing to lose productive spaces (Score 3 for amenity space).

Due to many soil-based systems being in open air, there is a concern that pollution in urban areas may increase pollutants within the crops. It has been found that older green roofs that have been planted with inedible plants have accumulated high levels of pollution in the growing medium over time which can then pollute urban water systems (Jarlett, 2013). A study in Berlin assessed the amount of trace metals taken up by edible plants in urban areas, where it was found that barriers from traffic (such as buildings and foliage) strongly reduces the heavy metal content of crops (Säumel et al., 2012). The study found that although most of the crops grown in the city had higher trace metal content than supermarket bought crops, the trace metal content of green beans, kohlrabi, basil and thyme where higher in the supermarket products compared to the field samples in the inner city, showing that supermarket products also contain trace metals (ibid) (Score 2 for pollution uptake). The choice and location of crops grown in cities is important for the health of urban dwellers. The run-off from green roofs should be monitored periodically in order to assess the level of pollutants, which can vary depending on the type and age of the growing medium (Harper, Limmer, Showalter, & Burken, 2015; Jarlett, 2013). Further research is needed on how urban crops are affected by air pollution and other pollution they are exposed to in urban areas. Soil-based systems are less reliant on a source of energy for the plants to survive, thus they use less energy and do not need power back up (Score 3 for reliance on fossil fuels and Score 3 for power back up).

The materials used for constructing and waterproofing a soil-based system will have an embodied energy, but much less high-embodied energy materials are needed in comparison to soil-less systems and a higher percentage of the material needed is compost/soil, which can have a low embodied energy if sourced within urban areas (Score 2 for embodied energy). Soil-based systems for cultivation on buildings can use compost made from urban municipal waste and build up a layer of nutrient-rich soilover time on a building, which could add to the much needed fertile soil on the earth (FAO, 2015) (Score 2 for soil as a finite resource). If an open-air soil based system is neglected, it will continue to function as a vegetated surface, with benefits such as; storm water retention, biodiversity, amenity space, shading building, alleviating the urban heat island effect and aesthetics (for people who think wild gardens look beautiful). They may also still function as productive spaces if perennial crops were planted such as herb bushes and fruit trees (Score 2 for resilience to neglect).

Table 3 shows that soil-based systems are not as productive per square metre as soil-less systems, thus reducing the amount of fresh produce available (Score 2 access to fresh produce). All types of crops can be grown in soil-based systems on buildings depending on the soil depth and climatic conditions, but it is more cost-effective to grow high value crops (Score 2 for crop types). The maintenance costs are lower for soil-based systems on buildings, as nutrients can be sourced for urban waste products and highly specialised staff are not required (Score 3 for maintenance costs).

Results of comparative analysis

Soil-less and soil-based systems for cultivating edible plants on buildings were introduced and given scores in the sections above using existing examples of systems. The analysis was underpinned by the triple bottom line

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Table 4 (a) **:** Soil-less system vs. soil based systems for cultivating edible plants on buildings. Points are given out of 3 for environmental, social and economic benefits to urban areas - **Environmental**

Criterion	**Soil-less systems**	**Soil-based systems**
	Environmental	
Can contribute to sustainable urban drainage	Yes if rainwater is collected (2)	Yes if not within an enclosed environment or rain water is collected (3)
Can contribute to alleviating the urban heat island effect	Not normally but yes if not within an enclosed environment (2)	Yes if not within an enclosed environment (3)
Ease of using organic fertiliser from urban waste streams	Low (1)	High (3)
Contribution to biodiversity	Not normally but a little if not within an enclosed environment (1)	A lot if not within an enclosed environment (3)
Water efficiency	High (3)	Medium (2)
Waste water is a pollutant to ecosystems and groundwater	No if treated (2)	No with management and monitoring (3)
Visual amenity	Not normally but high if the plants are clearly visible (2)	High if the plants are clearly visible (3)
Highly impacted by urban air pollution	Yes if not within an enclosed environment or barriers provided between source of pollution and growing space (3)	Yes if not within an enclosed environment or barriers provided between source of pollution and growing space (2)
Specialist nutrient solution needed in order to achieve nutrient rich produce	Yes (2)	No (3)
Reliance on fossil fuels for energy	High (reliance on fossil fuels can be low if renewable energy sources are used) (2)	Low (3)
Embodied energy	High(1)	Medium(2)
Back-up energy supply needed in case of power outages	Yes (2)	No (3)
Can grow crops in a range of climatic conditions	No (1)	Yes (3)
Soil as a finite resource	Opportunities to promote soil fertility restoration with appropriate management and policies (2)	Opportunities to promote soil fertility restoration with appropriate management and policies (2)
Reconnecting with the natural world	Low(1)	High(3)
Total environmental score (total score 45)	27(60% of total score)	41(91% of total score)

of sustainable development and the roles of urban agriculture for sustainable cities of the future. **Table 4** provides a summary comparison of soil-less systems and soil-based systems for cultivating edible plants on buildings. Using the scoring system, soil-based systems are 25% more beneficial overall to urban areas and on buildings than soil-less systems. Soil-based systems are 31% more environmentally beneficial for urban areas and on buildings, 33% more socially beneficial and equally economically beneficial in comparison to soil-less systems for cultivating edible plants on buildings.

Discussion: Key difference in benefits and methods of selecting systems

This paper has found that soil-based systems for culti-

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Table 4 (b) : Soil-less system vs. soil based systems for cultivating edible plants on buildings. Points are given out of 3 for environmental, social and economic benefits to urban areas - **Social**

Criterion	Soil-less systems	Soil-based systems
Social		
Specialist knowledge needed	High (1)	Low (3)
Social acceptance	Low (1)	High/Medium (2)
Resilience to neglect	Low (1)	Medium (2)
Provides an amenity space for urban dwellers	Not normally but yes with the loss of productive spaces (2)	Yes (3)
Increasing access to affordable, fresh produce	High if affordable (2)	Medium if affordable (2)
Total social score (total score 15)	7 (47% of total score)	12 (80% of total score)

Table 4 (c) : Soil-less system vs. soil based systems for cultivating edible plants on buildings. Points are given out of 3 for environmental, social and economic benefits to urban areas - **Economic**

Criterion	**Soil-less systems**	**Soil-based systems**
Economic		
Productivity	High if within an enclosed environment (3)	Medium/low depending on maintenance regime and skills level of gardener (2)
Cost to start up in comparison to each other	High (1)	Medium/low (2)
Cost to maintain in comparison to each other	Medium if well designed (2)	Low (3)
Weight	Low if open air, high if in an enclosed environment due to weight of structure (glass, steel etc.). Translucent plastic could reduce the weight. (2)	High (1)
All types of crops can thrive in the system	Yes but productivity per square metre for some crops is not cost effective (2)	Yes depending on the depth of the growing medium and the value of the crop (2)
Total economic score (total score 15)	10 (67% of total score)	10 (67% of total score)
Total overall score (total score 75)	44 (59% of maximum score)	63 (84% of maximum score)

vating edible plants on buildings are more beneficial for urban areas from an environmental and social perspective due to; the biodiversity benefits, providing amenity space, ease of using urban waste as a fertiliser to achieve nutrient rich produce, creating a connection with the natural world and basic level of knowledge needed to grow good quality produce. Soil-less systems for cultivating edible plants on buildings grown in controlled environments are much more productive per square metre than soil-based systems, thus they are able to provide much more local, fresh vegetables and fruit to urban areas, where these crops can be accessible to all

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communities if they are affordable. Making the crops affordable to everyone would increase the payback period for the capital invested in the system. If it is not possible to reduce the price of the produce for access to poorer communities, then it would be more beneficial to grow in a lower cost soil-based system if access to affordable fresh produce is priority for the given location as a soil-based system would also give the above environmental and social benefits.

The environmental, social and economic challenges for each site should be weighted in terms of priority in order to help with the decision of which system to use. For example, if access to green space, mental and physical health, healthy food literacy, biodiversity and affordability are priority in a particular urban community, then it may be more beneficial to use a soil-based system. In contrast, if productivity per square metre is important, such as growing on the rooftop of a supermarket in a wealthy area where other green spaces are available, then a soil-less system may be more beneficial.

The decision of using soil-less or soil-based systems can also be aided by looking at the location from an urban planning scale; dense urban areas may benefit more from soil-based systems on buildings due to the environmental and social benefits discussed above. Peri-urban areas such as suburbs may benefit more from some soil-less systems on buildings, as there are more green spaces available around the buildings. Access to local, fresh produce could be greatly increased for increasing urban populations. Depending on land values in peri-urban areas, it may be more financially viable to use a ground level space for soil-less cultivation.

Conclusion

This research has highlighted that:

- Soil-less systems are more productive per square metre, which increases the amount of locally grown, fresh produce available in urban areas.
- The produce grown in soil-based systems is more affordable than soil-less systems.
- Soil-based systems for cultivation on buildings are more environmentally and socially beneficial overall for urban areas than soil-less systems.

Future Research

This paper is only beginning the comparison of soil-less systems and soil-based systems for cultivating edible plants on buildings. Cultivating food on buildings and how we can do this is key to making every element of a city multi-functional and contribute to its sustainability and habitability. One criterion may be more important for a project than another criterion, for example for a business, productivity may be more important than amenity space. A study that weights the scores depending on the importance of each criterion for a given site may show which system would be more suitable for different projects.

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Conflict of Interests

The authors hereby declare that there are no conflicts of interest.

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